การศึกษากระบวนการอบอ่อนสำหรับลวดทองแดงขนาดเล็กที่ผ่านการรีดเย็น

นาย นรสิทธิ์ อังคศิริสรรพ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาการจัดการทางวิศวกรรม
ศูนย์ระดับภูมิภาคทางวิศวกรรมระบบการผลิต
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2542

ISBN 974-333-552-8

STUDY OF THE ANNEALING PROCESS FOR THE DRAWN FINE COPPER WIRE

Mr. Norasit Angkhasirisup

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering in Engineering Management
The Regional Centre for the Manufacturing Systems Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 1999

ISBN 974-333-552-8

Thesis Title	The Study of the Annealing Process for the Drawn Fine Copper Wire
By	Mr. Norasit Angkhasirisup
Department	Engineering Management
Thesis Advisor	Asst. Prof. Somchai Puajindanetr

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of Faculty of Engineering

(Associate Professor Tatchai Sumitra, Dr. Ing.)

THESIS COMMITTEE

....Chairman

(Professor Sirichan Thongprasert, Ph.D.)

....Thesis Advisor

(Assistant Professor Somchai Puajindanetr, Ph.D.)

....Member

(Ms. Nantaporn Leelaryonkul)

นรสิทธิ์ อังคศิริสรรพ : การศึกษากระบวนการอบอ่อนสำหรับลวดทองแดงขนาดเล็กที่ผ่านการรีดเย็น (STUDY OF THE ANNEALING PROCESS FOR THE DRAWN FINE COPPER WIRE) อ. ที่ปรึกษา : ผศ.ดร. สมชาย พัวจินดาเนตร, 87 หน้า ISBN 974-333-552-8

วัตถุประสงค์ของงานวิจัยนี้คือการศึกษาถึงพฤติกรรมของปัจจัยในการอบอ่อน ซึ่งมีผลกระทบต่อคุณสมบัติเชิงกลของลวดทองแดงที่ผ่านการรีดซึ่งใช้ในการผลิตสายไฟฟ้าแรงดันต่ำ ทองแดงขนาดเส้นผ่านศูนย์กลาง 8.0ม.ม. ถูกลดขนาดเส้นผ่านศูนย์กลางเป็น 2.6, 0.6, และ 0.08 ม.ม. ซึ่งมี %Cold work เป็น 89.44, 99.44, และ 99.99 % ตามลำดับ จากนั้น ลวดที่มีขนาดเส้นผ่านศูนย์กลาง 0.08ม.ม. ที่ผ่านการรีดนี้ จึงถูกอบอ่อน วิธีการที่ใช้อบอ่อนสำหรับการศึกษาในครั้งนี้คือ “Single phase-continuous electrical resistance annealing, 3-sheave type” โดยปัจจัยที่เกี่ยวข้องกับการอบอ่อนแบบดังกล่าวคือ แรงดันไฟฟ้า, ความเร็วลวด, และอุณหภูมิน้ำหล่อเย็น

ได้ทำการทดลอง 9 การทดลองสำหรับการอบอ่อนโดยแปรผันค่าแรงดันไฟฟ้าที่ใช้ในการอบอ่อนดังนี้ 25, 27, 29, 31, 33, 35, 37, 39, และ 41 และคงค่าความเร็วลวดและอุณหภูมิน้ำหล่อเย็นไว้ที่ 2,000 ม./นาที และ 50 องศาเซลเซียส ตามลำดับ โดยนำลวดที่ผ่านการรีดและอบอ่อนแล้วนี้มาทำการวิเคราะห์ โดยผลผลิตจากกระบวนการรีดและอบอ่อนจะถูกศึกษาในแง่ของคุณสมบัติเชิงกลและโครงสร้างทางจุลภาค ซึ่งได้แก่ %Elongation, Tensile strength, %Cold work, Grain size, และ Porosity

ผลการศึกษาพบว่า (1) การเพิ่มขึ้นของ %Cold work จะทำให้ Strength เพิ่มขึ้น แต่ %Elongation และ Grain size ในแนวพื้นที่หน้าตัด จะลดลง (2) %Elongation และ Grain size ของลวดที่ผ่านการรีดจะเพิ่มขึ้นหากค่าแรงดันไฟฟ้าที่ใช้ในการอบอ่อนเพิ่มขึ้นในช่วง 25 ถึง 39 โวล์ต (3) แรงดันไฟฟ้าที่เหมาะสม ที่ไม่ก่อให้เกิดการเปลี่ยนสีของลวดขึ้น คือ 37 โวล์ต และให้ค่า%Elongation เท่ากับ 24.1% (4) Porosityที่มีขนาดใหญ่และจำนวนมากนั้น ลด Strength ของลวด ซึ่งพบ ณ การทดลองที่ 33โวล์ต ซึ่งมี Porosity มาก โดยมี Strengthต่ำที่สุดคือ 24.28 ก.ก./ม.ม.^{2}

ภาควิชา ศูนย์ระดับภูมิภาควิศวกรรมระบบการผลิต	ลายมือชื่อนิสิต นรสิทธิ์ อังคศิริสรรพ
สาขาวิชา การจัดการทางวิศวกรรม	ลายมือชื่ออาจารย์ที่ปรึกษา ....
ปีการศึกษา 2542	ลายมือชื่อที่ปรึกษาร่วม ....

4171612021: MAJOR ENGINEERING MANAGEMENT

KEY WORD: Drawn fine copper wire/ Continuous electrical resistance annealing

NORASIT ANGKHASIRISUP: STUDY OF THE ANNEALING PROCESS FOR THE DRAWN FINE COPPER WIRE. THESIS ADVISOR: ASSIST. PROF. SOMCHAI PUAJINDANETR, Ph.D. 87 pp.
ISBN 974-333-552-8

The objective of this research was to study the behaviour of annealing factors, which affected on the mechanical properties of copper drawn wire used for producing low voltage cable. 8mm diameter of copper rod was reduced into 2.6, 0.6, and 0.08mm diameter, which were the percentage of cold work of 89.44, 99.44, and 99.99 %, respectively. The drawn wire of 0.08 mm, then, were annealed. The annealing method studied was the single phase-continuous electrical resistance annealing, 3-sheave type. The factors that involved with this type of annealing was the electrical voltage, wire speed, and coolant temperature.

For the annealing process, there were nine experiments, which were varied the annealing voltage at 25, 27, 29, 31, 33, 35, 37, 39, and 41, and fixed wire speed and cooling temperature at 2,000m/min and 50°C, respectively. The annealed drawn wires were analysed. The products of both drawing and annealing process were characterised for mechanical properties and microstructure being percentage of elongation, tensile strength, grain size, and porosity.

The experimental results found that (1) The increasing of percentage of cold work increased the tensile strength but decreased the percentage of elongation and grain size of cross-sectional area of drawn copper wire. (2) The percentage of elongation and grain size of drawn wire increased with the increasing of annealing voltage ranged from 25 to 39 voltage. (3) The appropriate annealing voltage, which the wire was not discoloration, was 37 volt and provided the percentage of elongation of 24.1. (4) The large size and high amount of porosity decreased the wire strength, which the lowest strength was 24.28 kgf/mm^2 found at the experiment of 33V that was mostly found the porosity.

ภาควิชา ศูนย์ระดับภูมิภาควิศวกรรมระบบการผลิต ลายมือชื่อนิสิต Norasit Angkhasirisup

สาขาวิชา การจัดการทางวิศวกรรม ลายมือชื่ออาจารย์ที่ปรึกษา ....

ปีการศึกษา 2542 ลายมือชื่อที่ปรึกษาร่วม ....

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to Asst. Prof. Dr. Somchai Puajindanetr, my advisor, for his constant guidance and advice me to make this study a success. I also wish to thank you committee members, Prof. Dr. Sirichan Thongprasert and Ms. Nantaporn Leelaryonkul for their comments and constructive suggestions, which helps me to have a broader perspective.

I express my sincere thanks to the Case study company for giving me the opportunity to carry out my study on its manufacturing process and providing all that I need for my thesis. A special thanks is extended to Mr. Vichan Kumthonkittikul, Mrs. Chommanard Pornwattanakul, Mr. Abdulmanan Phaichamnan, Mr. Noppadol, and other officers and operators of company.

Thank you so much to Dr. Roger N. Wright, Professor of Materials Engineering (Rensselaer Polytechnic Institute, Materials Science & Engineering Department, NY USA), for his kind assistance fax me the very useful papers of his research.

I am grateful to my parents and all of my family members for their endless support.

CONTENTS

Chapter

Chapter

LIST OF TABLES

LIST OF FIGURES

Figure

Figure

CHAPTER 1

INTRODUCTION

1.1 Background

This factory is the case study factory, which its products and application are interface cable assemblies, wire assemblies and wire hardness, flexible flat cable, magnetic lead assemblies for HDD, metal dome switch for mobile phone, and coaxial cable and telecommunication cable. The factory produces cable to support most of its products then the cable manufacturing in this factory is very important.

The factory produces both low and high voltage cables. For the low voltage cable, there are 51 series and it is more difficult to produce than high voltage cable because the small diameter size of each single wire for low voltage cable is easier to break than large diameter.

For the product of cable manufacturing of this factory, each product will be coded as follow

NN / N.NN TA:	NN	= The overall number of wire.
	N.NN	= The size of diameter of each wire.
	TA	= Annealed wire with tin coated (silver look)
	A	= Annealed wire without tin coated(copper look)

For example, 19/0.08 TA means that

- There were 19 single wires.
- The diameter of each single wire was 0.08 mm.
- Each single wire was annealed.
- And, each single wire was coated by tin.

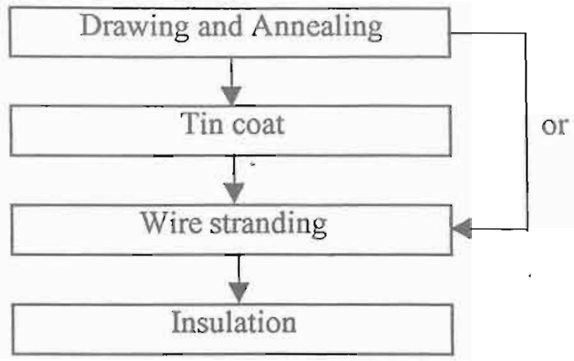


Figure 1.1: Cable Manufacturing Process.

1. Drawing process

This process is used to reduce the diameter of copper wire. Generally, this factory uses the 8 mm-diameter copper wire as the raw material and draws it to the 2.6 mm-diameter. This size of diameter is mostly use in the factory and will be drawn to the 0.6 mm-diameter then it will be drawn to the required diameter. The drawn wire has low elongation then it must be annealed to increase the elongation after the process of drawing from 0.6 mm to required diameter.

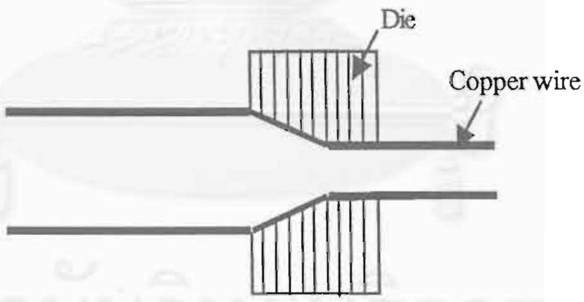


Figure 1.2: Deformation of Wire in the Drawing Process.

The elongation of the drawn wire is reduced when the percent cold work is increased, which the relationship can be illustrated by the following graph.

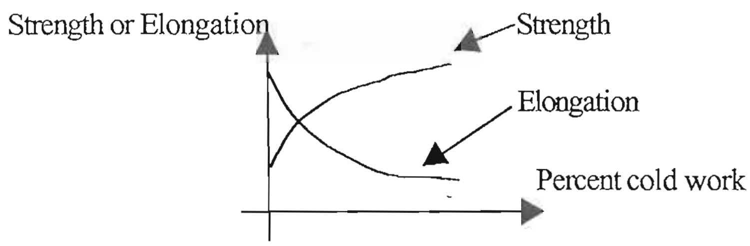


Figure 1.3: The relationship between Strength/Elongation and percent Cold Work

Then, the wire will be annealed to increase the elongation, which is shown in the following graph.

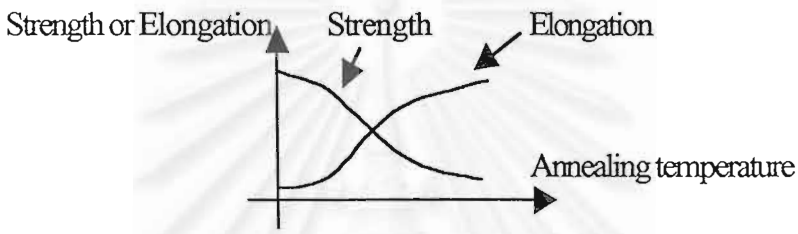


Figure 1.4:The relationship between Strength/Elongation and Annealing Temperature.

2. Tin coat process

The wire from drawing process will be coated by tin in this process. Some series of cable may not be coated, which depend on the order of each series. The elongation of coated wire will be reduced after pass this process. The following is the process of tin coat.

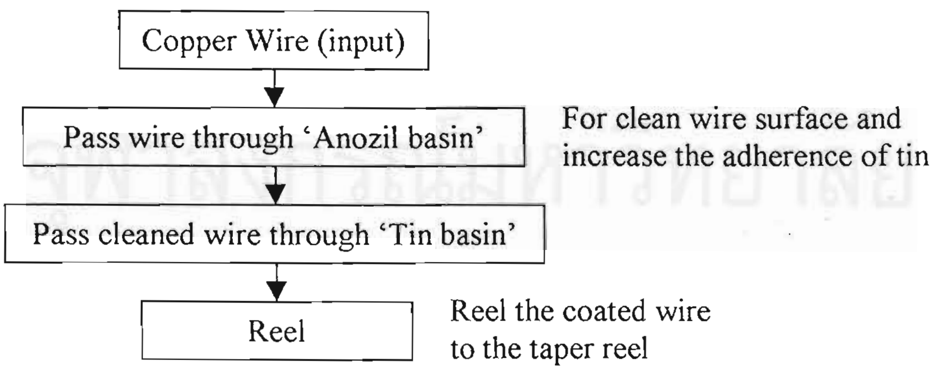


Figure 1.5: Tin coat process.

3. Wire stranding process

Each wire will be stranded together to be the conductor (cable that has no insulation). There are two methods of wire stranding. The first method is S-lay, clockwise direction. The second method is the anti-clockwise direction, Z-lay. Each method depends on the requirement of order.

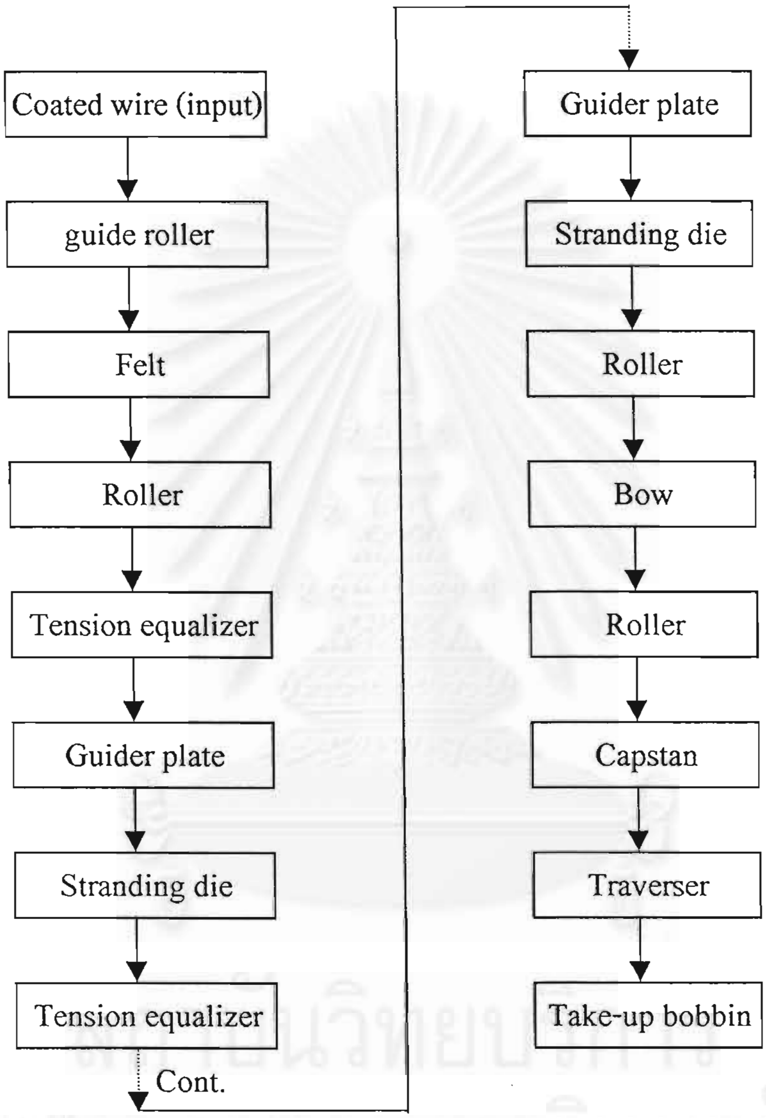


Figure 1.6: Wire stranding process.

4. Insulation process

The stranded wire is insulated by PP, PVC, and PE plastic in this process. The process of insulation is following.

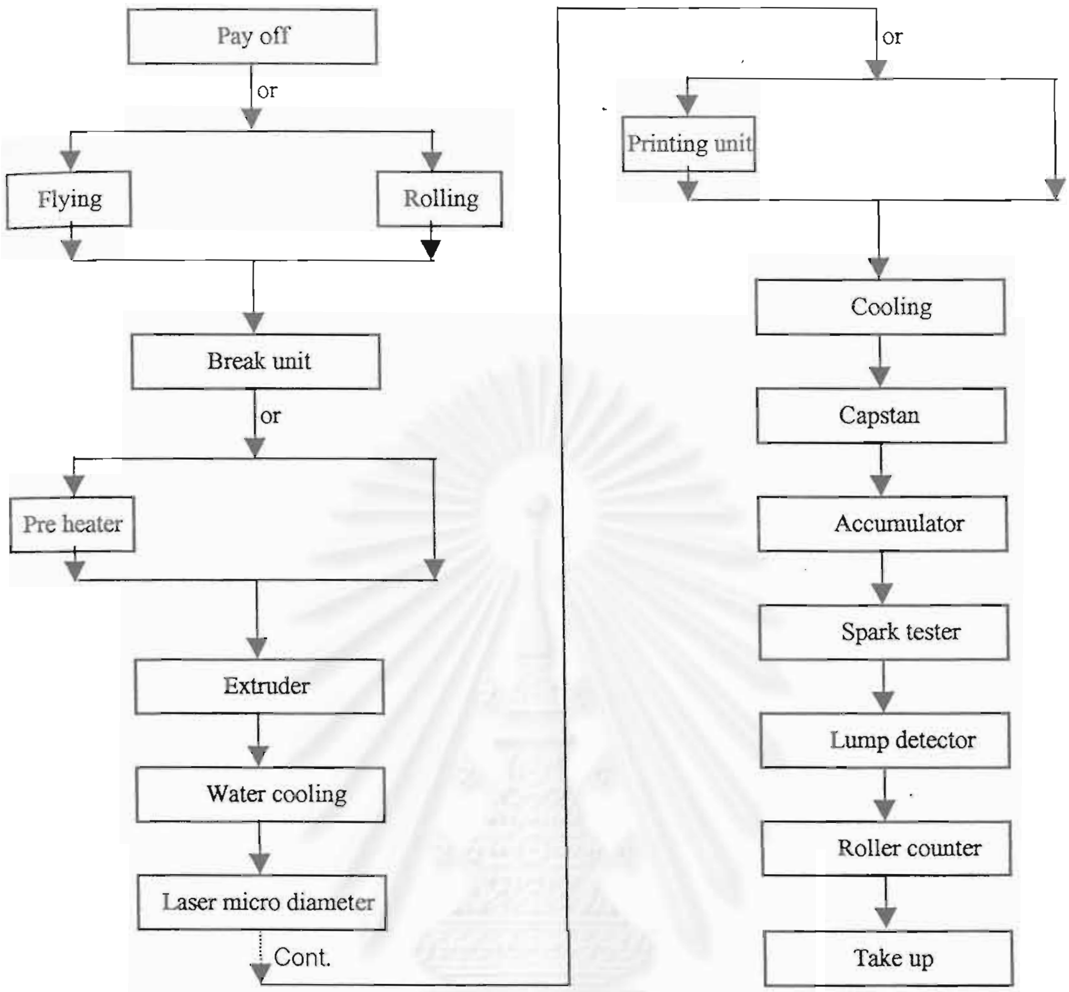


Figure 1.7: Insulation process

1.2 Statement of Problem

The wire break occurred in the insulation process, which was the final process of the cable manufacturing process. This obstructed the production and it was the result from the insufficient percentage of elongation of wire to withstand the pulled force of the process. In addition, elongation decreased after pass each process of cable manufacturing since drawing to insulation process.

The drawing process included the annealing process, which was the only one process that could increase the elongation for the wire. Therefore, the annealing process should be investigated.

1.3 Objective of the research

The objective of this research was to study the behaviour of annealing factors, which affect on the mechanical properties of copper wire used for producing low voltage cable.

1.4 Scope of the research

The implementation of this thesis focuses on the annealing process in order to find the elongation and strength of wire for the different annealing temperature, which based on 0.08 mm diameter copper wire with 99% cold work.

1.5 Methodology of research

1. Collect the related literature, the information of related content with this thesis from the World Wide Web and other documents.
2. Study the collected information.
3. Collect the information of the process, which include
   - The components and properties of raw material (8mm-diameter copper wire) and wire before and after annealing process.
   - percentage of cold working, percentage of elongation and strength of the copper wire before and after annealing, both 0.08 mm-diameter and other series in order to find the percent cold work that affect the mechanical properties.
   - Specification of annealing machine and the involved factors of the annealing process being annealing temperature, annealing time, and quenching temperature that affect the mechanical properties.
4. Find the result of annealing process from the data collection
   - Analyse the annealing process, its involved factors, and the percentage of elongation of annealed wire.
   - Compare the annealing process conditions with the existing condition.
5. Discussion and conclusion
6. Write up the thesis

1.5 Expected benefits

The expectation is to

- Observes the current process of annealing and quality of copper wire from the annealing process.
- Guide lines the process of annealing for the factory in order to improve the quality of copper wire from the annealing process.

CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Metal Forming Process

Metal forming process is the method that used to produce the metal as the required dimension by applying the force to the work piece. The stress and strain of metal will be increased very high to the plastic stage as a result of force applied. The shape of metal will then be changed to the direction of force result the new shape without the return though the force didn't be applied. Manut Satitjinda has divided the metal forming process into five processes as follow, which each process is divided by the type of applied force.

- Direct-Compression type Process: The force will be applied directly to the surface of work piece, which will be moved in the vertical with the force direction such as forging and rolling.
- Indirect-Compression Process: The force will not be applied in the vertical with the work piece surface but the work piece will be pulled through the die, which will then cause the compressed force between die and work piece such as extrusion and wire/ tube drawing.
- Tension-type Processes: The force will be applied to stretch the work piece as the shape of die such as stretch forming.
- Bending Process: The forces will be applied to the work piece from both side of die.
- Shearing Process: The shearing force will be applied to the work piece to cut the work piece to be the shape required.

For the temperature factor during the forming process, there are two major types, which are hot working and cold working. However, the Warm working is available for the forming process that requires the temperature between hot and cold.

"Indirect-Compression Process" is the process that related with the thesis and it is the cold working process, which the temperature required during the forming process is lower than the recovery or recrystallisation temperature of the metal. In addition, the strain will be occurred after the forming process without disbandment. The results are that the increment in strength and reduction in ductility or elongation (Harold Hattersley (1995) Elongation is a measure of the material's ductility, which should high enough to withstand the elongate force during the process.), which both factors depend on the percentage of cold working.

After the cold working process, the annealing process is required in order to increase the ductility however the strength will be reduced. The temperature and time used in annealing affect the structure of metal, ductility, and strength. Manut Satitjinda has suggested that if the annealing temperature used is between 0.3 times and 0.5 times of melting temperature, the strain still existing called recovery. But, if the annealing temperature used is higher than 0.5 times of melting temperature, the mechanical properties will be vastly changed result the decrease in strength and the elongation will be increased as the direct ratio with time. The details of wire drawing process (cold working) and thermal processing (annealing process) will be discussed as follow.

2.2 Wire Drawing Process

Michael J. McNulty (1995) has defined the wire drawing process that is *"the process of producing the wire from a rod breakdown line is drawn down to smaller diameter, annealed in a continuous resistance annealer and packaged onto a spool for further processing"*. The final diameter produced depends on the type of drawing machine used and the diameter of the wire being put into the wire drawing line.

As a result of cold working effect, the ductility (elongation) decrease, tensile strength increase, and electrical conductivity reduce. In addition, the internal microstructure of the cold drawn wire will be heavily deformed and elongated in the direction of drawing. The mentioned cold drawn wire is changed in both mechanical and physical properties. Therefore, if these changes keep continued by doing the wire drawing, the wire breaks and cracks will occur as a result of building up of residual stress and internal defect. The graph in Figure 2.1 shows the effect of area reduction upon tensile properties of copper wire.

The size of wire can be defined by referred to the AWG size, which is shown in Table 2.1. The wire diameter used in the studying of the annealing process of the thesis is referred to the AWG size as the 40 AWG, which represents that the bare wire diameter is about 0.079mm (0.0031inches).

The wire drawing process is a process included in the process of producing the flexible insulation cable, which the production steps used to produce the flexible insulation cable suggested by Michael J. McNulty (1995) are shown in Figure 2.2.

Due to Figure 2.2, the wire used to study in this thesis is produced similar to these steps, which the studying is concentrated in the wire drawing process. As mentioned above that the wire drawing process includes the annealing process therefore the details of annealing process will be mentioned following.

2.3 Annealing Process

Horace Pops (1995) has defined heating of nonferrous metals that is a general topic covering several different types of metallurgical processes, which are activated by heat. And, these are the processes range from annealing, which is the elimination of effects caused by different methods such as solution heat treating and quenching, or dispersion hardening.

Annealing is the process of heating up the wire to an evaluated temperature in order to bring about the significant change in microstructure or property. Annealing process involves a very board range of heating rates, soak times, temperatures, and cooling rate. The process is to eliminate the effects caused by cold working of the metals, through the hardening and strengthening of the metals by different methods such as solution heat treating and quenching, or dispersion hardening.

Therefore the drawing and annealing are the significant steps in the development of the desired combination of properties of wire produced.

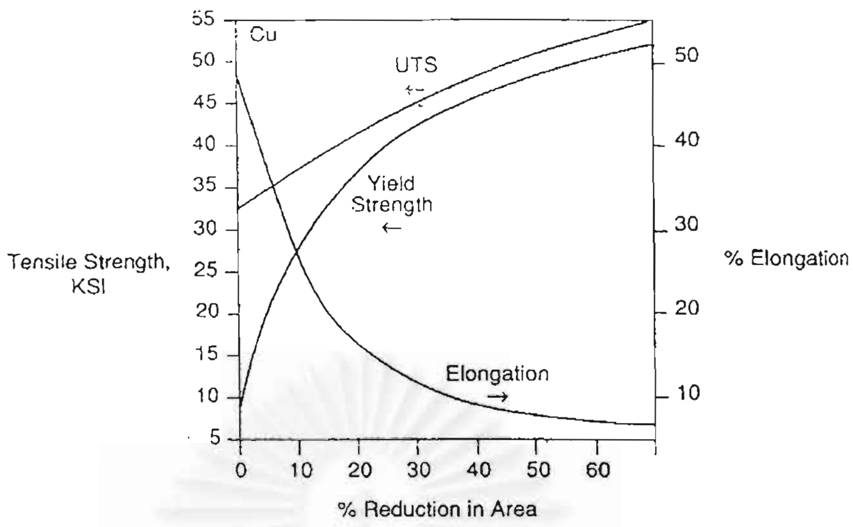


Figure 2.1: Effect of area reduction upon tensile properties of copper wire.

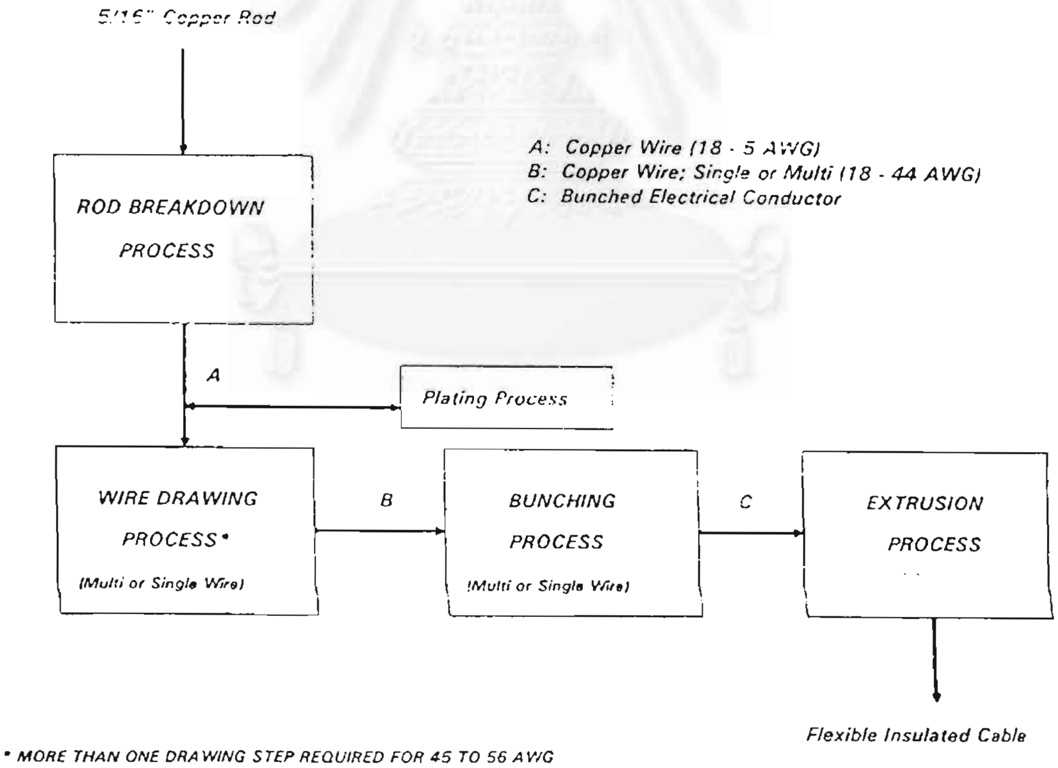


Figure 2.2: Production Steps; flexible insulated cable

Table 2.1: The AWG Sizes of the Round Bare Copper Conductors.

Nominal Areas And Dimensions Of Round Bare Conductors. Whole AWG Sizes. Values At 20°C.

From NBS Handbook 100—Copper Wire Tables
National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161 USA

AWG SIZE	BARE WIRE DIAMETER		CROSS SECTIONAL AREA (A)		(B)	AWG SIZE
	(inches)	mm	CIRC. MILS	SQ. mm	SQ. MILS	
5/0	0.5165	13.119	266772	135.18	209523	5/0
4/0	0.4600	11.684	211600	107.23	166200	4/0
3/0	0.4096	10.404	167772	85.01	131800	3/0
2/0	0.3648	9.266	133079	67.43	104500	2/0
1/0	0.3249	8.251	105560	53.48	82910	1/0
1	0.2893	7.348	83690	42.41	65730	1
2	0.2576	6.543	66370	33.62	52120	2
3	0.2294	5.827	52630	26.67	41330	3
4	0.2043	5.189	41740	21.15	32780	4
5	0.1819	4.620	33090	16.77	25990	5
6	0.1620	4.115	26240	13.30	20610	6
7	0.1443	3.665	20820	10.55	16350	7
8	0.1285	3.264	16510	8.367	12970	8
9	0.1144	2.906	13090	6.631	10280	9
10	0.1019	2.588	10380	5.261	8155	10
11	0.0907	2.304	8226	4.168	6461	11
12	0.0808	2.052	6529	3.308	5128	12
13	0.0720	1.829	5184	2.627	4072	13
14	0.0641	1.628	4109	2.082	3227	14
15	0.0571	1.450	3260	1.652	2561	15
16	0.0508	1.290	2581	1.308	2027	16
17	0.0453	1.151	2052	1.04	1612	17
18	0.0403	1.024	1624	0.8229	1276	18
19	0.0359	0.912	1289	0.6531	1012	19
20	0.0320	0.813	1024	0.5189	804.2	20

Table 2.1: The AWG Sizes of the Round Bare Copper Conductors (Continued).

AWG SIZE	BARE WIRE DIAMETER (inches)	BARE WIRE DIAMETER mm	CROSS SECTIONAL AREA (A) CIRC. MILS	CROSS SECTIONAL AREA SQ. mm	CROSS SECTIONAL AREA (B) SQ. MILS	AWG SIZE
21	0.0285	0.7240	812.300	0.411600	637.9	21
22	0.0253	0.643	640.100	0.324300	502.7	22
23	0.0226	0.574	510.800	0.258800	401.2	23
24	0.0201	0.511	404.000	0.204700	317.3	24
25	0.0179	0.455	320.400	0.162400	251.7	25
26	0.0159	0.404	252.800	0.128100	198.6	26
27	0.0142	0.361	201.600	0.102200	158.4	27
28	0.0126	0.320	158.800	0.080450	124.7	28
29	0.0113	0.287	127.700	0.064700	100.3	29
30	0.0100	0.254	100.000	0.050670	78.54	30
31	0.0089	0.226	79.210	0.040140	62.21	31
32	0.0080	0.203	64.000	0.032430	50.27	32
33	0.0071	0.180	50.410	0.025540	39.59	33
34	0.0063	0.160	39.690	0.020110	31.17	34
35	0.0056	0.142	31.350	0.015890	24.63	35
36	0.0050	0.127	25.000	0.012670	19.64	36
37	0.0045	0.114	20.250	0.010260	15.9	37
38	0.0040	0.102	16.000	0.008107	12.57	38
39	0.0035	0.089	12.250	0.006207	9.621	39
40	0.0031	0.079	9.610	0.004869	7.548	40
41	0.0028	0.071	7.840	0.003973	6.158	41
42	0.0025	0.064	6.250	0.003167	4.909	42
43	0.0022	0.056	4.840	0.002452	3.801	43
44	0.0020	0.051	4.000	0.002027	3.142	44

The materials and supplemental systems of the process include wire drawing dies, wire drawing lubricant, wire, annealing quench, spools (bobbins), utilities (electricity, compressed air, stream or nitrogen, cooling water, etc.), wire string-up devices, wire welders and systems for supplying and filtering the wire drawing lubricant.

Horace Pops (1995) Heating of drawn wire produces property changes in the conductor through reduction (but not complete elimination) of these lattice defects, starting with point defects, continuing with line defects, and ending with the removal of some grain boundaries. *If hardening is carried to completion, all properties may be restored to their original values, or become nearly the same as those measured prior to cold work* (drawing).

The graphs in Figure 2.3 represent the typical annealing curves for hard drawn wire, Horace Pops (1995) *if the drawn wire are heated to a fixed temperature and followed with periodic measurement of different properties, or if they are annealed for a fixed time at several different temperatures.*

From the graph in Figure2.3, there are three separate regions that occur sequentially in the annealing for hard drawn wire, recovery, recrystallisation, and grain growth.

Recovery: The driving force for this region is a reduction in the thermodynamic energy different between the deformed state and the recovered structure. It involves the annihilation of atomic vacancies and the rearrangement of dislocations. Thus, only the most sensitive physical properties are affected (such as a reduction of resistance), and no change in microstructure can be seen in the optical microscope. Although mechanical properties, such as hardness, strength, and elongation remain unchanged, residual stresses are usually eliminated. Most strain-free regions that form during recovery can serve as the origin or nucleus for subsequent annealing.

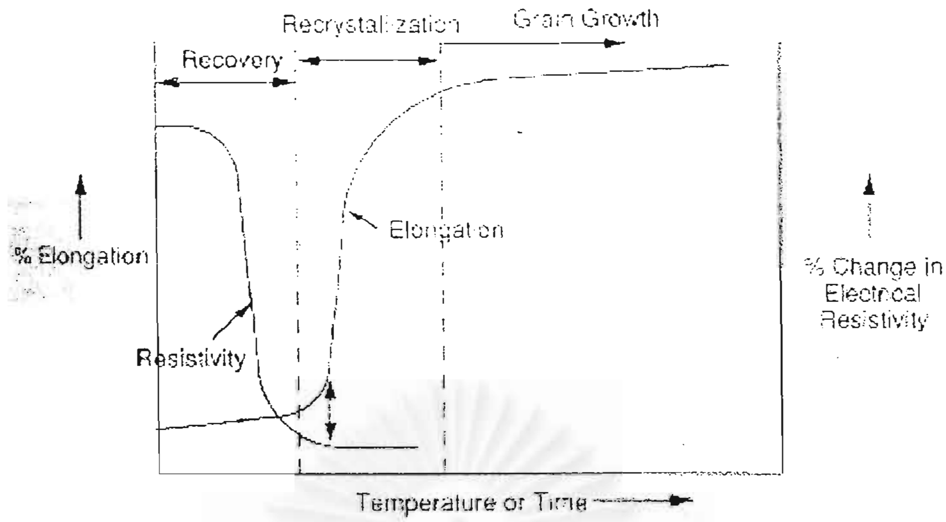


Figure 2.3: The regions that occur sequentially in the annealing for hard drawn wire.

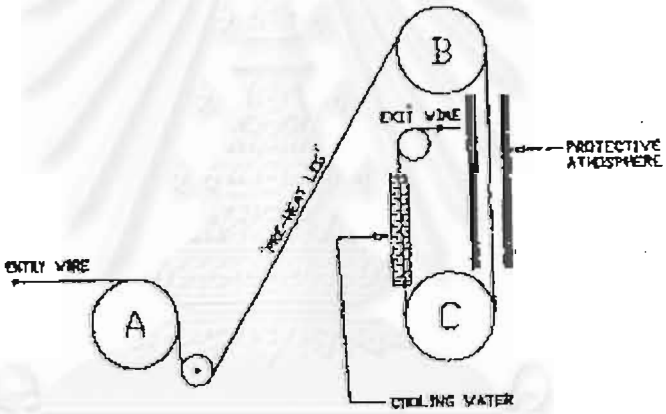


Figure 2.4: Single-Phase Annealer

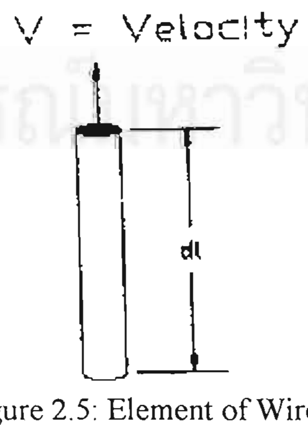


Figure 2.5: Element of Wire

Recrystallisation: The driving force for this process is the decrease of free energy, which is accomplished through the reduction of the dislocation network remaining after recovery. From the figure 2.3, it can be seen that in this stage the wire elongation undergoes rapid and sudden changes from the as-drawn value to the dead soft or fully annealed property.

It should be noted that during the period when new grains are forming, the surrounding deformed matrix might continue to undergo recovery. Recrystallisation progresses rapidly by the nucleation and growth of new grains, but slows down considerably when the advancing annealed grains impinge upon each other.

Grain Growth: The previous annealing process (also known as primary recrystallisation) is considered to be complete when all deformed by new grains, and all properties are restored to their original values. As the heating process continues, however, a slow but gradual growth of the polycrystalline grains occurs. This progressive grain growth is driven by an atomic mechanism that reduces the grain boundary area, and, therefore, the surface free energy of the conductor.

There are two most common methods of annealing hard drawn conductors in the wire industry employ either the batch process or continuous electrical resistance annealers.

Harold Hattersley (1995) In-line resistance annealing of wire is a process in which the wire is heated in a protective atmosphere while moving at some line speed in order to change the microstructure to provide desired mechanical and electrical properties.

For copper wire, the specimen that has been cold drawn to area reduction in excess of 93 percent increases in tensile strength to around 60 to 65 KPSI and ductility (elongation) reduces to less than 1.5 to 2 percent.

As mentioned above that there are two principle methods of annealing, continuous electrical resistance annealing is the process used of the factory, therefore, this process will be much more described in details rather than the other one.

2.3.1 Batch Annealing

Batch annealing inclines to be an isothermal (constant temperature) annealing process, and the controllable parameters are holding time and temperature (The wire is held at a constant temperature for specific periods of time, to achieve the required degree of anneal.). Although each variable is important, the recrystallisation process is much more sensitive to slight temperature changes than to variations in time at a fixed temperature. The adjustable parameter is temperature and time, which are easily controlled. However, this process is not attractive for high-speed production as most factory. The reasons are listed as follow.

- Very time-consuming.
- Easier to occur non-uniform annealing.
- Inefficiently use of energy

2.3.2 Continuous Electrical Resistance Annealing

Continuous electrical resistance annealing is usually incorporated after wire drawing process, and the important adjustable parameters are wire speed and applied voltage. The principle of the process obeys Ohm's law therefore the wire moving over pulleys or sheaves that act as electrical contacts supplying the heating power is heated. The wire attains its maximum peak temperature in the annealing leg just as it reaches the last contact pulley (sheave).

Harold Hattersley (1995) There are several methods used to apply the voltage to the moving wire listed as follow.

1. **Direct**-In this method, the wire moves over pulleys or sheaves which are electrically connected via brushes or mercury contactors to transformer or other source of electrical power. The wire therefore becomes a direct part of the electrical circuit. This

method is commonly used because of the lowest manufacturing cost. It utilises simple physical concepts, easy to maintain, and reasonably energy efficient. However, the energy losses occur as follow

- Heat losses from the wire to the sheave and to the environment (radiation and convection).
- Electrical power lost through brush voltage drops.
- Friction between annealing contacts against brush friction.
- Bearing and seal friction (water pump action)

2. **Induction Resistance**-In this method, a special transformer is used wound in such a manner as to facilitate the passage of wire through the magnetic field so that the wire forms the secondary of the transformer circuit. The energy used for this method is very efficient because there is no brushes, belts and drive pulley thereby the current passes through the wire and not through the sheave. Therefore, the longer life of contactor is improved. However, the separate cooling section and the special transformer are required and these may cause a problem.

3. **Straight Induction**-The moving wire to be annealed passes through the centre of a special multi-turn coil formed by winding a conductor (generally copper) so that the moving wire is placed at the centre of strong magnetic field. A high frequency source supplies power to the induction coil, which in turn transfer the power to the wire by transformer action. This method is not necessary for the wire to make contact with any sheaves for heating purpose. Therefore the surface damaged is eliminated. However, the cost of special equipment for annealing is too high and the separate cooling section and oxidation-free environment are required.

Due to the 3 methods metioned, the first method, Direct method, is the method used by the case study factory. In addition, refer to Harold Hattersley (1995) p69 *"The most popular type of electrical resistance annealer is the direct type."* Therefore, the details of direct type will be addressed further.

- **Direct Resistance Annealing**

Currently, there are two types of direct resistance annealing available, which are

- Single-phase design
- Multi-phase design (Three-phase design)

The concept of Single-phase design annealer (See Figure 2.4) are that the wire will be heated in two steps, which the first step is preheat leg and the second is anneal leg. The purpose of preheat leg is to reduce the thermal shock (because the additional time to heat wire is provided before enter the anneal section) when initially heat the wire from the normal temperature. In the pre-heat section, the wire is generally open to the environment therefore the wire temperature must not be too high to cause the discoloration. After preheat leg, the wire will be heated again to the desired temperature in the anneal leg. In the annealing section, the stream or nitrogen must be used to enclose the wire in order to prevent the discoloration of wire at the annealing temperature.

Multi-phase design is used to anneal the large wire size. The concept of multi-phase design is similar to the single-phase design but a great number of sheave is required.

2.4 Cooling Process

Harold Hattersley (1995) The wire is cooled in most resistance annealers by direct contact with water and/or sheaves immersed in heater, therefore the cooling mechanism is one of both convection (water contact) and conduction (contact with sheaves or idler wheels).

In the convection process, it is importance to have turbulent flow patterns to aid in breaking up the vapour (stream) barrier surrounding the wire to achieve high convection coefficients.

The conduction heat transfer, which occurs between the wire and sheaves or wheels immersed in water is an coefficient way of eliminating the problem of vapour barrier formation and therefore generally accounts for the most significant portion of the cooling occurring in modern day annealers.

Harold Hattersley (1995) suggested that *"the cooling, quench, water temperature is also extremely important and if it rises above 120°F (48.9°C), will usually result in ineffective cooling. To ensure a reasonable margin of safety, it is generally best to maintain quench temperature between 85 and 95°F (29.4 and 35° C)."* In addition, Harold Hattersley also suggests the range of quench temperature as follow *"the quench water temperature should be maintained within ± 3 to 5°F of a given setting."*

For the concentration of water-soluble oil, it is generally used in low quantity, less than one percent. The one- percent of oil is not affect the heat transfer and it is also improve the spooling and eliminate sticking of wire.

In addition, the level of quench water, in some annealer, should be maintained sufficiently high in the annealing zone in order to prevent the oxidation, which may affect the annealing voltage required. The quench temperature is necessary to ensured at the temperature appropriated when starting state or the annealing may be start operating when the quench temperature reach the steady state value.

Harold Hattersley summarises the consideration for the proper design of the quench section as follow

1. Maximising heat transfer
2. Good controls of quench temperature by proper selection of heat exchangers and temperature control valves.

3. Effective control of water level in the annealing zone, even at changing wire speed.

2.5 Guidelines for the Annealing of Nonferrous Wire

The useful guidelines for annealing of nonferrous wire were summarised as follow.

- Time and temperature should be consulted for the required annealing schedule. Longer times are always needed at lower temperature for the same degree of recrystallisation.
- The percent of cold work prior reduction in area affects the recrystallisation temperature that if the amounts of cold work increase, therefore, the recrystallisation temperature decrease and the number of lattice defects increase.
- Metal impurities have extremely large effect upon the recrystallisation process. All residual impurities and alloying additions raise the temperature required for annealing.
- The cooling rate (from the annealing temperature) is usually of minor importance, particularly for high purity metals. At the high level of certain impurities, the fast cooling rates from elevated temperatures may keep these eliminate retained in solid solution and therefore make the annealing process more sluggish.
- The recrystallisation process can be affected by the amount of prior cold work, heating rate, impurities content, annealing temperature, holding time, and grain size. Therefore, the value of temperature should be considered only as approximation. The increase of annealing temperature attributed to impurities for copper is quite large.
- At the amount of cold work prior to annealing that higher than 90 percent reduction in area, the unfavourable annealing textures form in copper wires, thereby increasing the recrystallisation temperature and strength. In addition, both of these effects are undesirable for any annealing process.

2.6 Calculation Method

2.6.1 Percentage of Cold Work

As mentioned previously in the wire drawing process topic that the copper wire is changed in cross-sectional area as a result of cold working, the change in cross-sectional area could be measured by calculating the percentage of cold work (percentage of reduction in area). The calculation formula is following.

$$\%\textbf{Cold work} = (A_0 - A_f) \cdot 100/(A_0)$$

Where: A_f is the final cross-sectional area.

A_0 is the initial cross-sectional area.

2.6.2 Tensile Strength and %Elongation

Tensile strength is the stress that corresponds to the maximum load in a tensile test.

$$\textbf{Strength} = F/A_0$$

Where: **F** is the max load applied to the specimen.

A_0 is the cross-sectional area of specimen.

The ductility measures the amount of deformation that the material can withstand without breaking. Percentage of Elongation describes the extent to which the specimen stretches before break.

$$\%\textbf{Elongation} = (l_f - l_0) \cdot 100/l_0$$

Where: l_f is the distance between gage after test.

l_0 is the initial distance between gage before test.

2.6.3 Annealing Temperature

The annealing temperature could be calculated by using the equations from Nonferrous wire handbook (1995) pp.71-74, which the basic concepts were following.

The calculation considers the wire in each element, finite length "dl" (See Figure 2.5), as it moves through the annealer shown in Figure 2.4. The following formulas were used for calculating the estimation temperature.

$$T = (\sigma_i/\theta)[(e^{(K_2 \times t)}) - 1] + T_i$$

Where: T = Temperature of element after time "t" (°F)

(The temperature of the wire is an exponential function of the time t)

T_i = Initial temperature of wire (°F)

θ = Temperature coefficient of resistance (Ohm-in./°F)

σ_i = Initial resistivity (Ohm-in.) @ temperature T_i

; $\sigma = \sigma_i + \theta\,(T - T_i)$

K_2 = Constant = $(\theta \times K \times I^2)/(C \times \rho \times A^2)$

; K = Conversion factor from electrical energy to heat energy (BTU/sec. Watt)

I = Current of Pre-heat leg and Anneal leg (Ampere)

C = Specific heat for copper (BTU/ lb.°F)

ρ = density of copper (lbs./in.^{3})

A = cross-section area (in.^{2}) = $(¶/4)\,d^2$

At the constant velocity (constant wire speed) the relationship between t and L is linear and therefore the temperature of the wire is increasing exponentially along the path L between electrical contacts (sheaves).

t = time = L/V

; L = length of wire between contact sheave and point of interest (Pre-heat leg and Anneal leg)

V = Wire velocity (in./sec, m./min)

2.7 Copper Alloy (Sherif D. El Wakil (1998))

Copper was one of the first metals to be used by human because it could be found in its metallic form. Now, it is seldom to find copper in its pure form, and it is usually extracted from ores that contain only 5% copper by weight. Copper and its alloys have excellent electrical and thermal conductivity as well as corrosion resistance. In addition, copper has excellent ductility. The preceding properties make copper the ideal metal for electrical conductors. In fact, more than 80% of all copper produced is used in the form of pure copper; the remainder is used in many alloy forms. The major alloying elements in copper alloys include zinc, tin, and nickel. These are included in copper to change the properties as desired.

2.8 Literature Review

Bhambri, A. K., King, M. G., and Spence, G. I. (1997)

This paper describes an alternate method consisting of Differential Scanning Calorimeter for determining recrystallisation / annealing behaviour of copper rod. The correlation of recrystallisation peak data with spiral elongation number and the application of this technique in monitoring annealability of copper rod during production.

Carlsson, B. and Huml, P. (1996)

The paper represents the material properties of cold-draw wire. The wire is not the same in the drawing direction as in the radical direction, due to texture development. The anisotropy usually remains in the material after annealing and has therefore an effect on subsequent forming operations.

De Palma, G. (1998)

For this paper, a study was conducted to make the cable production cycle simpler through the elimination of operations with no added value and the reduction of raw material costs. Several possible alternatives were considered. The best alternative was to divide the process in two phases. The first phase was wire-drawing / bunching, with out annealing, followed by the second phase of high speed insulation, with in-line annealing of previously produced hard strand.

The science and engineering of materials.

Donald, R. A.

The information that is useful for the thesis is about cold working and annealing. For the cold working, wire drawing is a subject that is discussed. It is the simultaneous process of deformation and strength the alloy by pass the wire through the die. The rough effect of cold work on the mechanical properties of copper shown as the diagram, which represent that the increase in percent cold work will effect the mechanical properties in term of reduce in percent elongation and increase in strength. For the annealing, it is a heat treatment that used to eliminate the effect of cold working. This represents the three stages of annealing (recovery, recrystallisation, and grain growth) that depend on the annealing temperature.

Frank F. Kraft, Roger N. Wright, and Udayachandran Chakkingal (1991)

This paper is addressed the process metallurgy and to quantify the annealing response of electrolytic tough pitch (ETP) copper wire in terms of process parameters and time and temperature by the continuous resistance annealing process. The paper intents to present the development of useful analytical methods, process simulations, and testing techniques to provide specific relationships between process parameters and physical and mechanical material properties. It is also intended that this work be general enough for application to the widest range of electrical resistance annealing equipment available.

The paper can be concluded that

- The peak temperature that the wire reaches in a typical industry annealed can not be measured.
- Annealers of this type are typically set up in production using operator/industry experience.
- If heat losses are neglected, the thermal history of the wire is relatively easily calculated in terms of the general process parameters-wire size (AWG), line speed, length of annealing and pre-heat legs and voltage.

Frank F. Kraft and Roger N. Wright

The paper is about the equations, which more accurately model the heating and cooling cycle imposed on the wire by the continuous electrical resistance annealing process.

The equation suggested for the peak temperature in the leg of annealing is following.

$$T = d\cdot[(e^{(b(t+c)}) - a]$$

Where

$a = I^2\sigma_0(1-\alpha T_0) + h_c * p * A * T_\infty)/(A^2 * \rho * C_p)$

$b = (I^2 * \sigma_0 * \alpha - h_c * p * A * T_\infty) / (A^2 * \rho * C_p)$

$c = d\cdot\ln|a+bT_0|$

$d = 1/b$

The equation is assumed that

- Convection is the dominant heat transfer mechanism.
- Conduction effects along the wire's axial length are negligible.
- Omission the radiation losses.

Inakazu, N., Kaneno, Y., and Inoue, H. (1994)

The paper describes the parameter of optimum setting period of an intermediate annealing in production line, fibre texture formation on a drawing process of fine copper wire. This has been analysed by means of the x-ray diffraction and transmission electron micrography.

Kim, Y. T., Jang, J. Y., Kang, C. H., and Hahn, K. H. (1990)

The study investigated the effects of subsequent processing variables after rod fabrication on the flexibility of copper wire. The experiment showed the amount of deformation before annealing in order to obtain an enamelled wire good flexibility.

Manut Satitjinda; Lecture sheet, Chulalongkorn University

The method of deforming processes and its effect are discussed, including the advantages and disadvantages of cold working. The plastic characteristic and effect of speed of deformation on forming processes are another subject that involves.

Menge, R. (1991)

This paper objective is a precise as possible estimate of the temperature variation over the annealing section in the combined drawing and annealing of copper alloy and composite wires. This is the basis for extended considerations the design of combined drawing and annealing installations for the contemplated range of material.

The properties of engineering materials

Raymond, A. H.

The non-ferrous metals and alloys topic is the topic that discuss about the copper and its alloys, which represents the characteristics of copper, the diagram, and some example of micro-structure of copper and its alloys.

Principles of materials science and engineering

Smith, W. F.

The information is about the metal forming process includes the wire drawing and method of calculates the percent cold work. The mechanical properties of metals are also discussed, which include the elongation, the cold plastic deformation of metal, and the change in tensile strength and elongation vs. percent cold work. The effect of annealing on the structure and mechanical property changes of a cold worked metal are a topic that discussed.

Wright, R. N. (1996)

A basic discussion of texture (preferred grain orientation) in copper wire is set forth, including the roles of deformation and annealing, methods of characterisation, practical significance, and related process variables and process optimisation. Also, the relation of die angle to texture and annealing response is summarised, and the implications for processing for minimisation of springback are examined.

CHAPTER 3

EXISTING PRODUCTION PROBLEMS

Due to the background in Chapter1, percentage of elongation was very significant for the wire production because there was the pulled forces applied to the wire in each production process and then the percentage of elongation of wire would be decreased as a result of production method. The percentage of elongation value was used to indicate the capability of wire to be elongated.

3.1 Existing Production Problems

During the process of insulation, this final process always stopped because of the wire break, especially, when operated the small diameter wire. A cause of wire brake in this process was that the wire has no enough elongation in order to withstand the pull force.

There were 51 series of cable that had to be insulated by the insulation machine. The following are the top three consumption of the insulation process in 1997, April 1997 to March 1998. (As the experience of planning division, these always the top three consumption in each year.)

Table 3.1: The top three consumption of the insulation process in 1997.

Sequence of series	Series	Consumption (kms.)	Percent Consumption	Percent Accumulative
1	7/0.12TA	127,383	31.56	31.56
2	19/0.08TA	112,900	27.98	59.54
3	7/0.16TA	84,382	20.91	80.45
4	The rest 48 series	78,906	19.55	100.00
	Total	403,571	100.00	

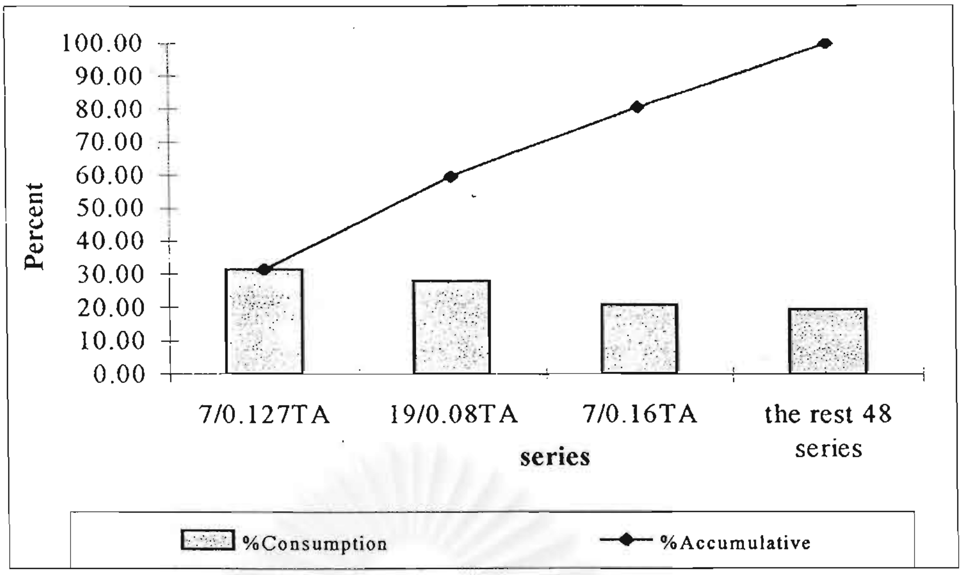


Figure 3.1: Pareto of Consumption in 1997.

The method of data collection for the number of wire break was changed and the new method would be used by December 1998, and then the data of wire break before December 1998 could not be used. The following is the data of wire break from December 1998 to February 1999.

Table 3.2: Data of wire break from December 1998 to February 1999.

Month	Kms/time		
	7/0.12TA	19/0.08TA	7/0.16TA
Dec.'98	127.71	**19.23**	93.64
Jan.'99	51.57	**28.13**	87.51
Feb.'99	73.38	**39.57**	84.44

As the data above, 19/0.08TA was the series that was the second most consumption and occurred the highest defects. Also, the planning division plans that the consumption trends of this series increase. Then, this series was chosen to investigate.

The elongation would be decreased after pass each process since tin coat process to the insulation process. Then, the process before the insulation process should also be investigated.

The investigation in the wire-stranding process showed that the wire break also occurred in this process and the elongation also a cause of wire break in this process.

The elongation was significant for this process because the capstan pulls the wire then each single wire would be elongated. The single wire that had no enough elongation will then break but some of them might not be found in this process. The defect conductor that sent to the next process, insulation process, would then cause the problem. Also, the single wire that broke in the wire stranding process and was not detected would clog at the nipple of insulation process because the overall surface of conductor was not smooth and it could not pass the nipple.

For the tin coat process, this process also reduced the elongation of each single wire. The factory set the lowest elongation for this process at 10%, which the wire that had lower elongation than this figure would then rejected because it would cause the wire break. From the data collection, the data were between 9.45 and 15.75 percentage of elongation, which there was the reject. The average elongation of coated wire was 12.49%. However, the standard deviation of the data was 0.92 and there were some wires that its elongation was lower than the specification and the wire could be checked only at the end of overall wire, which the elongation in each period of length was not the same.

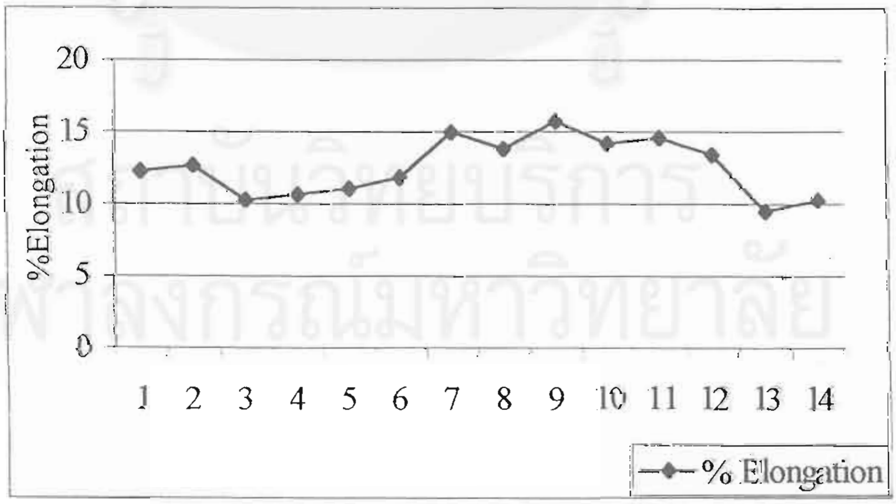


Figure 3.2: Percentage of Elongation of wire from the tin coat processes.

For the drawing process, the wire was drawn from 8mm to 0.08mm, which the percentage of cold work was 99%. The 0.08mm wire would then annealed, which the specification of wire from the drawing process was set at the 15% elongation. The data collections of elongation in this process were between 16.36 and 17.06% elongation, which was shown in the following graph. The average of these data was 16.6% and the standard deviation was 1.98. However, wire could also be checked only at the end of bobbin as tin coat process.

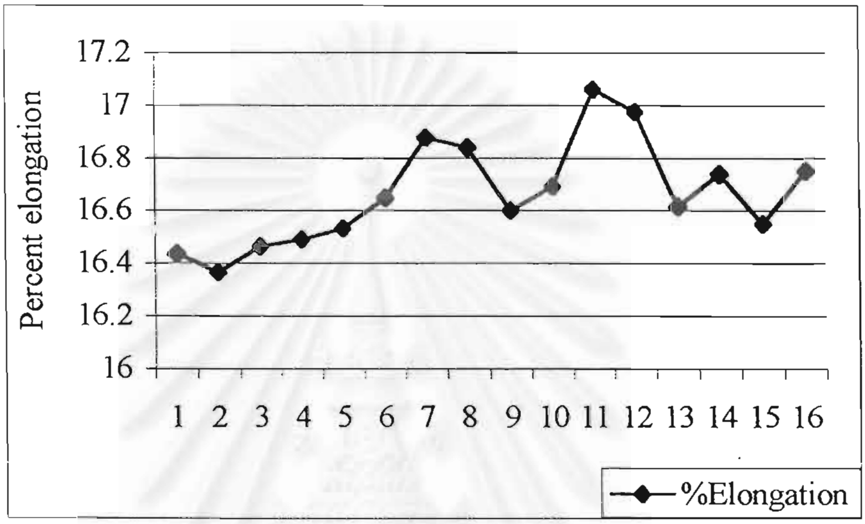


Figure 3.3: %Elongation of wire from the annealing process

For the annealing process, the factors that involved with the percent elongation were annealing temperature and coolant temperature. The factory set those factors as follow

- Voltage = 33±0.5 Volt, Current = 17±1.0 Ampere
- Coolant temperature = 60-65 °C

Generally, the data of tin coat and drawing were collected by production department (not found lower spec product). But, the data of tin coat as shown above were collected by the engineering department, which can detect the reject product. For the data of drawing, there were no data collections by the engineering department, which might be found the lower spec product if collected by this department.

From the data above, the elongation of the wire in each process was near the specification. If the percent elongation were increased, the possible of wire break would then be reduced.

3.2 The Conditions of Annealing Machine for the Existing Production

The details of material, drawing machine, and annealing machine were shown in Chapter 4. The conditions of the annealing machine for the existing production were set as follow.

➢ ***Input voltage***	***33V.***
➢ ***Wire speed***	***2,000 m/min.(1,312in/sec)***
➢ Running length per bobbin	532 km. (approximately)
➢ Length of wire in pre-heat section	820.42 mm. (32.3in.)
➢ Length of wire in annealing section	112.78 mm. (4.44in.)
➢ Length of wire in cooling section	159 mm. (6.26in.)

➢ Cooling section: 1 % concentration of oil in water

♦ Turbulent condition during operating.	
♦ Flow rates	110 L/min.
♦ ***Temperature set of coolant in tank***	***60°C***
♦ Actual temperature in (measured)	50°C
♦ Actual temperature out (measured)	59-60°C

From the conditions above, the factors that directly related with the annealing result were the input voltage, wire speed, and coolant temperature (See Figure 3.4). The input voltage could be set within the range between 25 and 41V. This factor would then be varied for the experiment in order to find the different of annealing result for each input voltage (See details in Chapter4).

For the wire speed, the speed was set at the maximum speed of the machine, which was 2,000m/min. The wire speed relates directly with the productivity. If the wire speed was set lower than the maximum speed, the productivity would be dropped. The maximum speed would then be required in order to maintain the maximum productivity. Therefore, this factory would not be adjusted or decreased.

The cooling system was set the cooling temperature at 60°C, which was the lowest temperature that it could be. This was the result of the system that could not cool down the temperature of coolant drain because there was no cooler to cool down the coolant temperature but there was only the heater. In addition, the temperature of coolant drain was about 60°C, therefore, the heater was never be operated in the existing condition. This factor would then not be varied in the experiment.

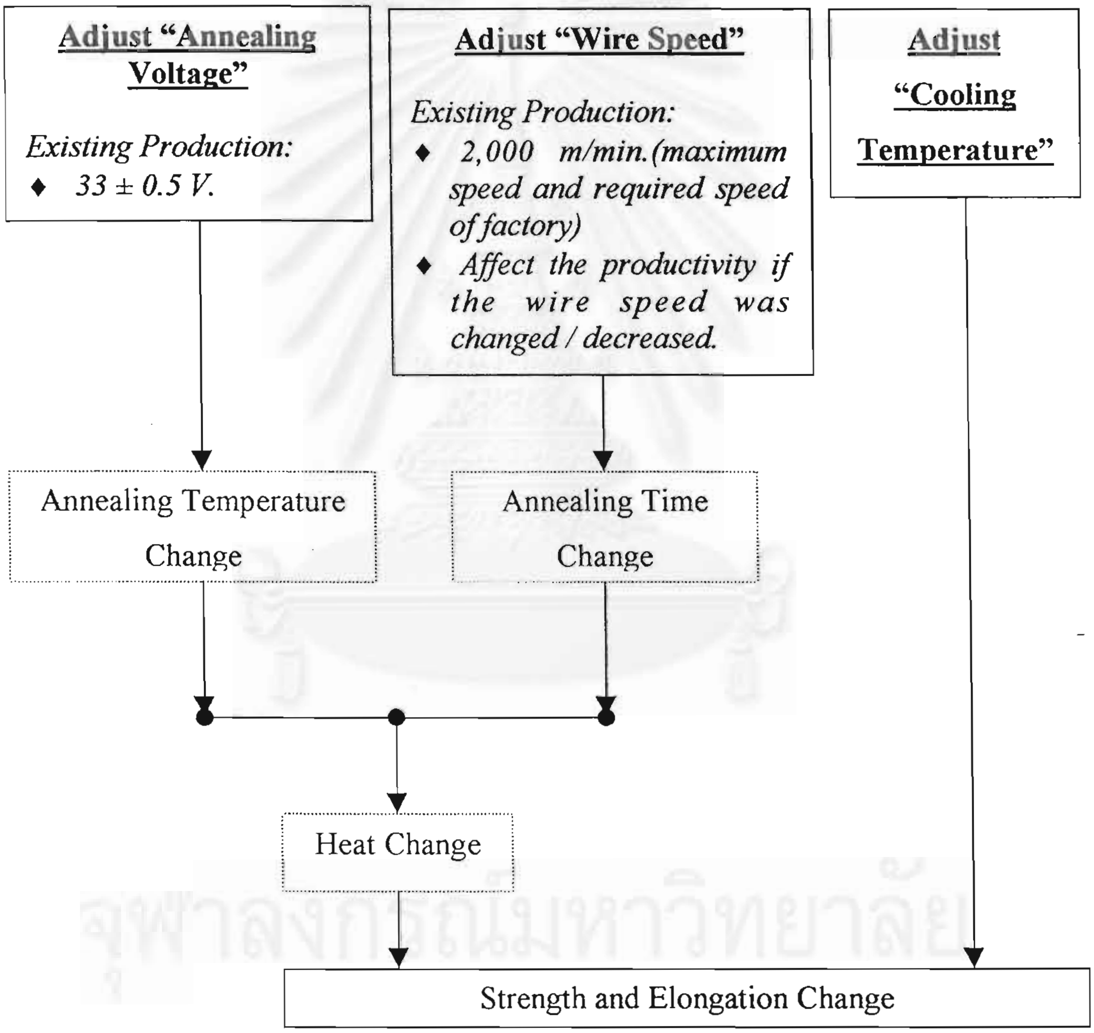


Figure 3.4: Diagram of the processing factors affecting the strength and elongation.

CHAPTER 4

EXPERIMENTAL METHODS

The experimental methods of this study can be divided into two groups, drawing method and annealing method. There are three drawing machines used for the drawing process, G-class, F-class, and SF-class, and one annealing machine for annealing process. The 8.0mm diameter of copper rod would be firstly drawn to the diameter required, 0.08mm diameter, by those three machines and it would then be annealed by the annealing machine. The overall experimental methods are shown in Figure 4.1.

4.1 Material and Equipment

4.1.1 Material

- Soft Bare Copper Rod (See Figure 4.2)
  - Type: Electrolytically refined tough pitch copper (ETP-Copper)
  - AWG size 1/0 (Approximately)
  - Diameter 8.0 mm. (0.3149in.)
  - Same lot of raw material used during the experiments.
- Specification and Composition of Copper rod (See Table 4.1, 4.2)

4.1.2 Copper Wire Production Equipment

Copper wire production process in this study consists of 1) drawing machine and 2) annealing machine, which the details of both machines are following.

1. **Drawing machine**

   (a) Brand: SHOWA; G-Class drawing machine (See Figure 4.3)

   - Model: AH-11+VC-610
     - The numbers of maximum dies for this machine are 11 dies and the diameter of vertical coiler is 610mm.

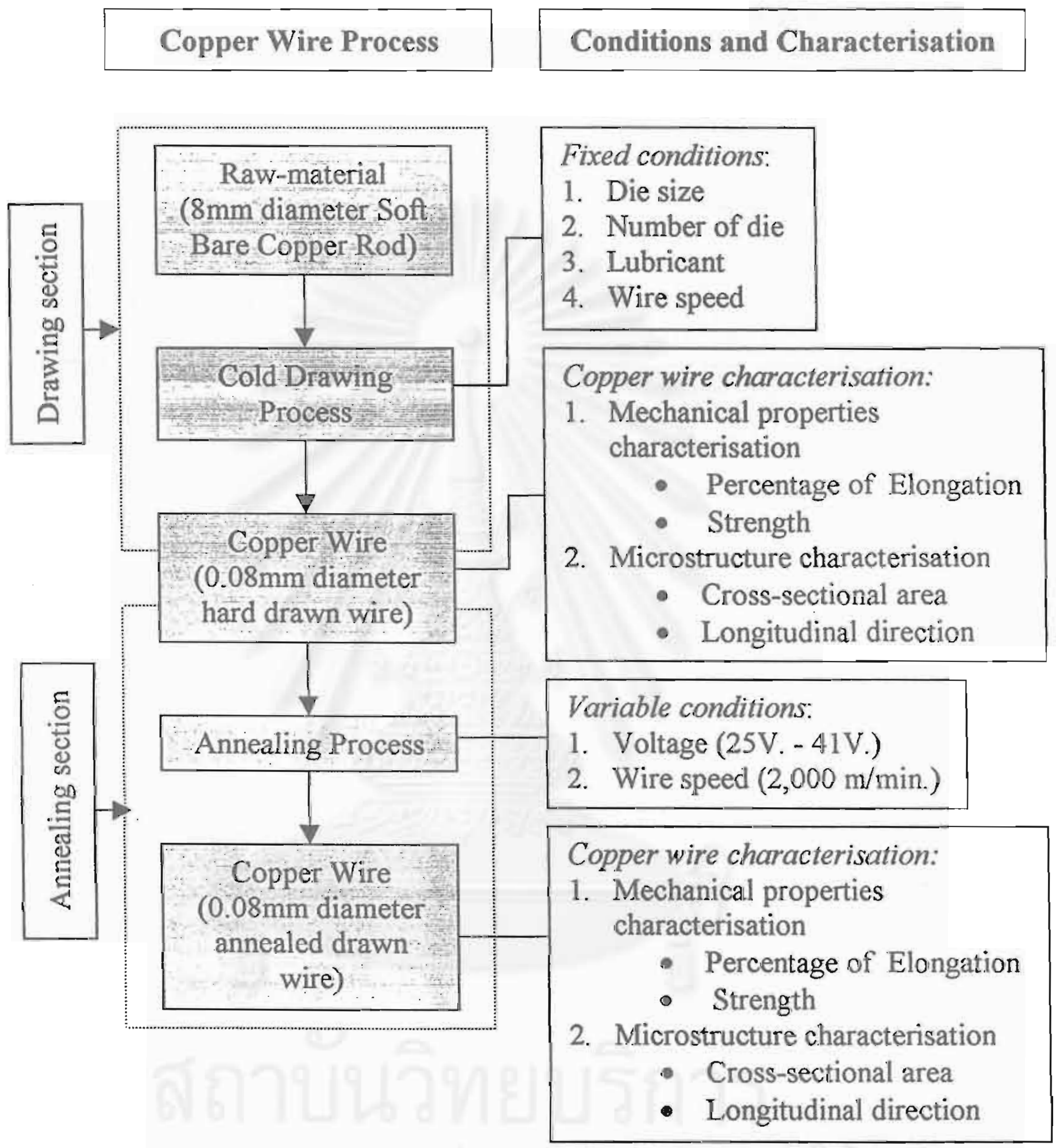


Figure 4.1: Experimental diagram

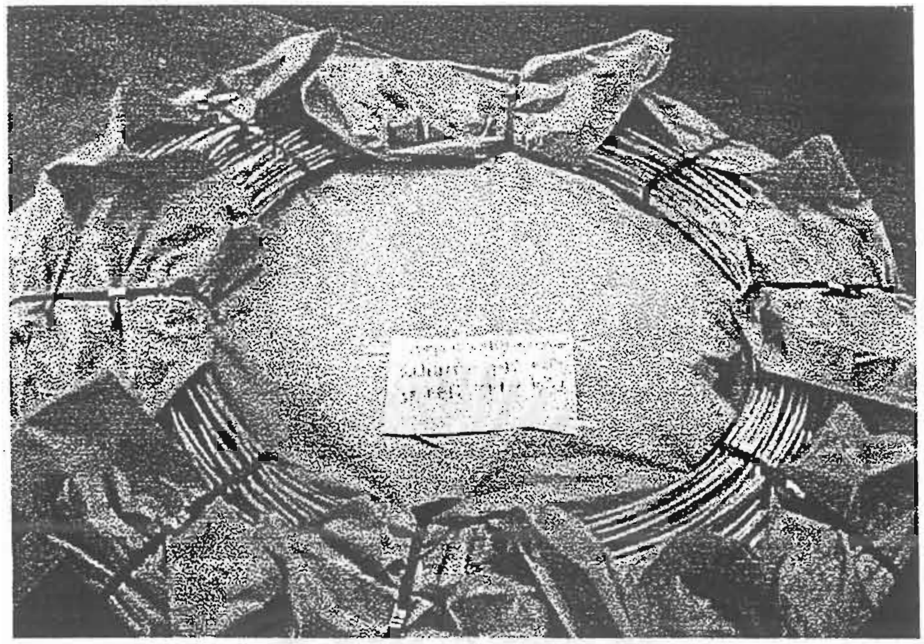


Figure 4.2: 8mm. diameter; Soft Bare Copper Rod (Raw material).

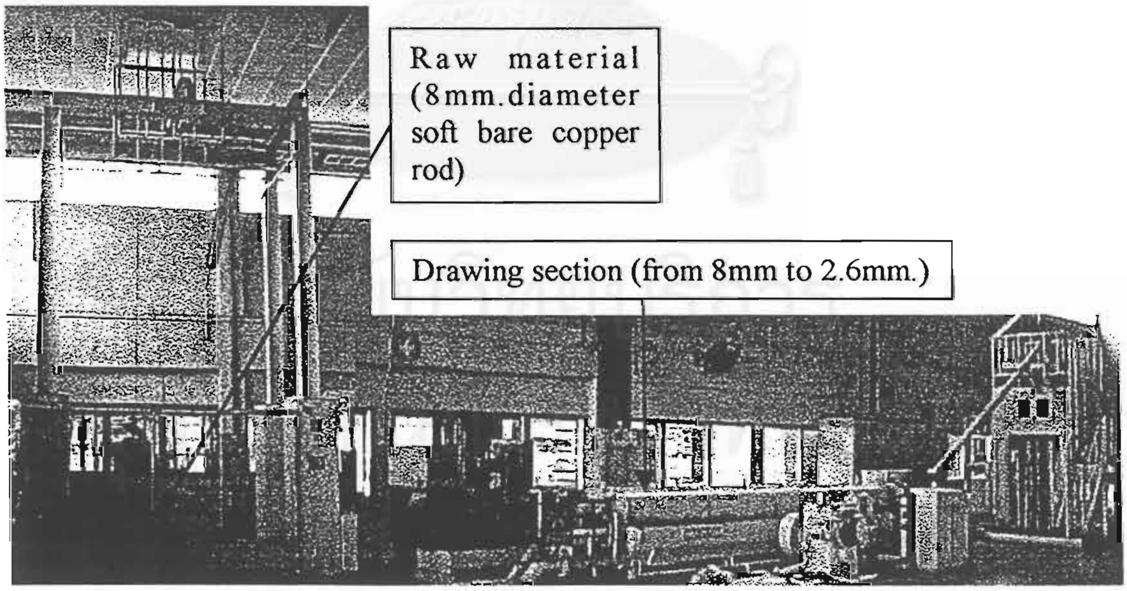


Figure 4.3: G-Class drawing machine.

Table 4.1: Specification of Copper Rod 8 mm. diameter (Tested by supplier)

Test Items	Unit	Spec.	Test Result		
			Max. value	Min. value	Mean value
Appearance	-	As Spec.	Good		
Diameter of wire	mm.	7.62-8.38	8.08	8.00	8.043
Conductivity at 20°C	%	Min.100	101.50	101.40	101.47
Tensile Strength	Kgf/mm^2	Max. 27	24.20	24.00	24.10
Elongation	%	Min. 30	42.70	40.70	41.43
Copper	%	Min. 99.90	99.96		

Table 4.2: Composition of Copper Rod 8 mm.-diameter (Tested by supplier)

Assay Certificate	Unit	Spec.	Results
Cu	%	Min. 99.90	99.96-99.97
Ag	PPM	25	5.99
As	PPM	5	2.13
Bi	PPM	1	<0.70
Fe	PPM	10	<1.0
Ni	PPM	10	<0.40
Pb	PPM	5	<1.0
S	PPM	15	1.16
Se	PPM	2	<0.541
Sb	PPM	4	<2.0
Sn	PPM	5	<2.0
Te	PPM	2	<2.0
O	PPM	100~650	257~360

- There are 9 dies used for this machine. The die schedule is shown in the Table 4.3.
- ➢ Type: Drawing machine without annealing set.
- ➢ Function: Drawn 8.0mm. diameter to 2.6 mm. diameter.

(b) Brand: SAIKAWA; F-Class drawing machine (See Figure 4.4)

- ➢ Model: CH-17+S-250+VD-560
  - The numbers of maximum dies for this machine are 17 dies and the diameter of spooler and vertical coiler are 250 mm and 560 mm, respectively.
  - There are 13 dies used for this machine. The die schedule is shown in the Table 4.4.
- ➢ Type: Drawing machine without annealing set.
- ➢ Function: Drawn 2.6mm. diameter to 0.6 mm. diameter.

(c) Brand: SAIKAWA; SF-Class drawing machine(See Figure 4.5, 4.6)

- ➢ Model: SA-20 (No.DW-411)
  - The numbers of maximum dies for this machine are 20 dies.
  - There are 20 dies used for this machine. The die schedule is shown in the Table 4.5.
- ➢ Type: Drawing machine with annealing set.
- ➢ Function: Drawn 0.6mm. diameter to 0.08mm. diameter.

2. Annealing machine

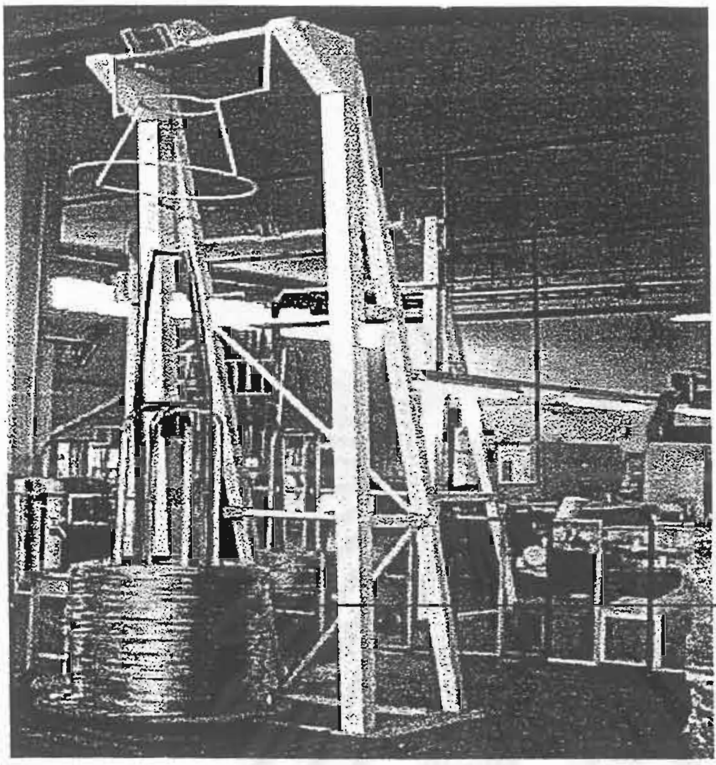
The model of annealing machine used for the experiment was the same machine model used for the daily production. It was the machine that includes both drawing system and annealing system. The machine selected was coded DW-411.

Table 4.3: Die schedule for G-Class drawing machine

Die number	Die diameter (mm.)
1	7.2
2	6.0
3	5.4
4	4.7
5	4.2
6	3.7
7	3.3
8	2.9
9	2.6

Table 4.4: Die schedule for F-Class drawing machine

Die number	Die diameter (mm.)
1	2.30
2	2.00
3	1.75
4	1.55
5	1.40
6	1.25
7	1.12
8	1.00
9	0.90
10	0.81
11	0.73
12	0.66
13	0.60



2.6mm.diameter from G-class drawing machine supplied to F-class drawing machine.

Drawing section of F-class drawing machine.

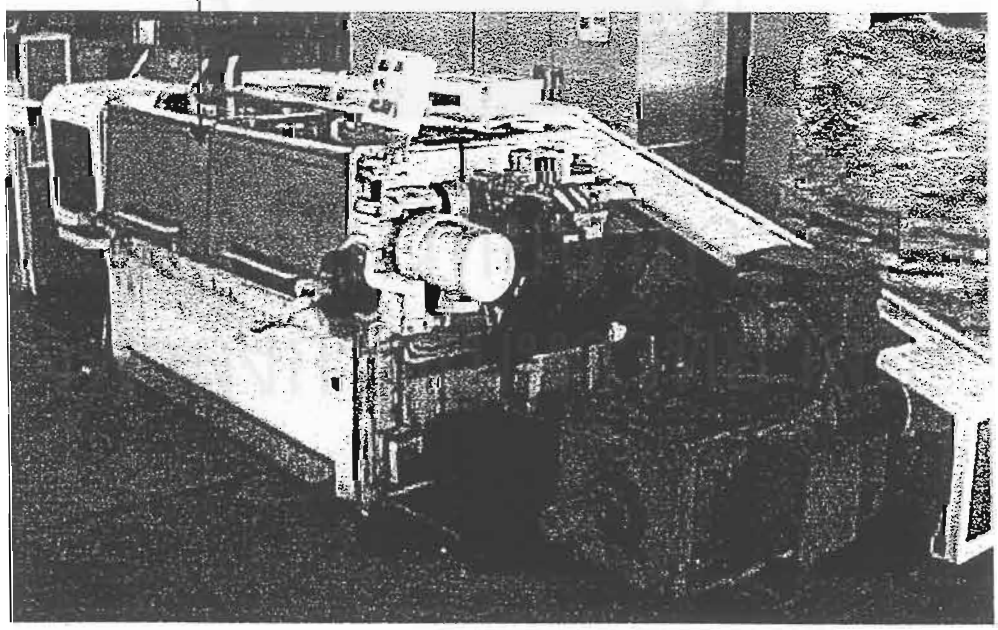


Figure 4.4: F-Class drawing machine.

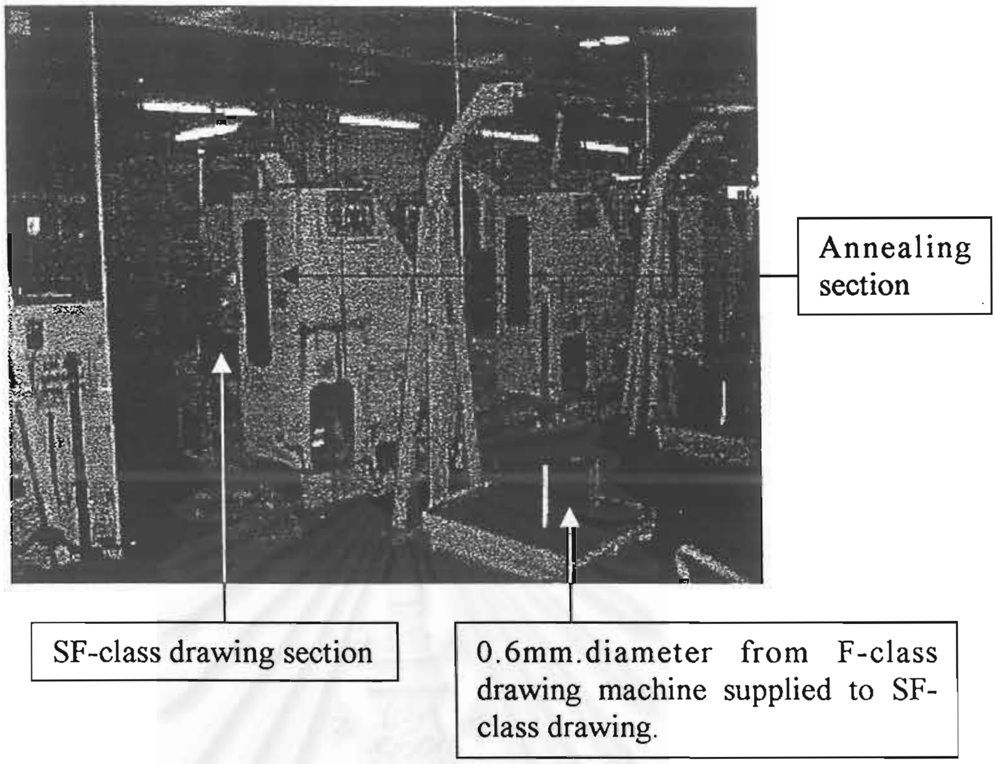


Figure 4.5: SF-Class drawing/ annealing machine.

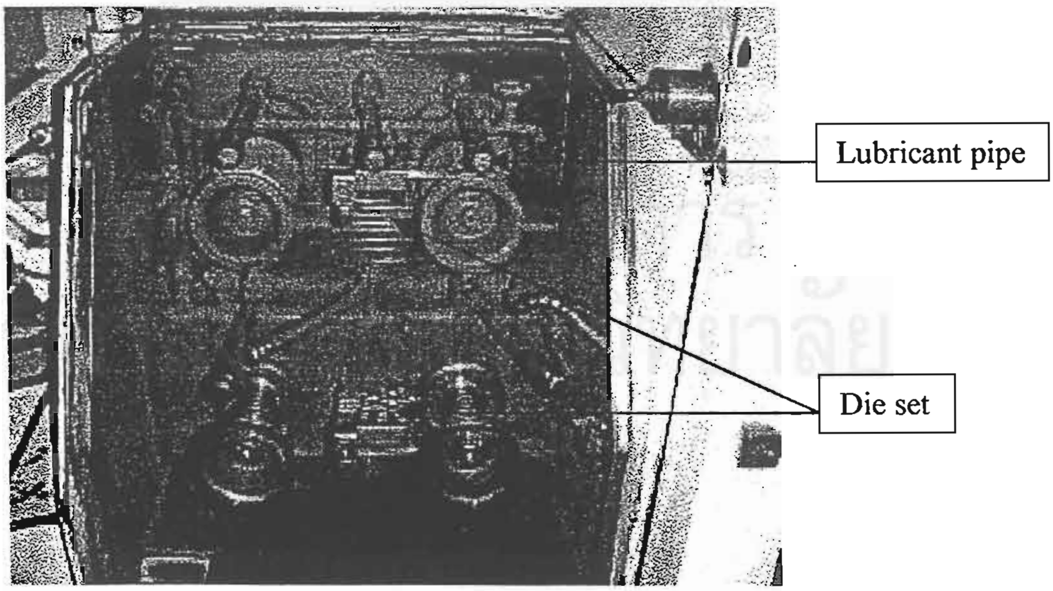


Figure 4.6: SF-Class drawing section.

Table 4.5: Die schedule for SF-Class drawing machine

Die number	Die diameter (mm.)
1	0.525
2	0.461
3	0.405
4	0.359
5	0.32
6	0.285
7	0.257
8	0.231
9	0.211
10	0.193
11	0.175
12	0.16
13	0.146
14	0.134
15	0.123
16	0.113
17	0.104
18	0.096
19	0.089
20	0.082

The annealing machine used in this study was the machine that was supplied the 0.08mm diameter of hard drawn wire from the SF-class drawing machine. The type of annealing system was the single phase-continuous electrical resistance annealing, 3-sheave type. The method used to apply the voltage to the wire of this machine is "Direct method". The model and function of machine is following

- Brand: SAIKAWA (See Figure 4.5, 4.7)
  - Model: SA-20
  - Function: Anneal 0.08mm diameter of hard drawn wire.

The machine could be separated into five sections shown as follow.

1) Heating section (Annealing section) (See Figure 4.7)

- Copper sheave: electrical pole
  - Diameter 100 mm.
  - 1st and 3rd sheave are the - pole.
  - 2nd sheave is the + pole.
- Pre-heat section
  - Length (Distance between 1st and 2nd copper sheave , fixed) 820.42 mm.(32.3in.)
- Annealing section
  - Length (Distance between 2nd copper sheave and point before enter the cooling section, fixed) 112.78 mm.(4.44in.)

2) Guide and Support section (See Figure 4.7)

- Plastic roller (white colour)
  - Diameter 7 mm.
  - Diameter 9 mm.

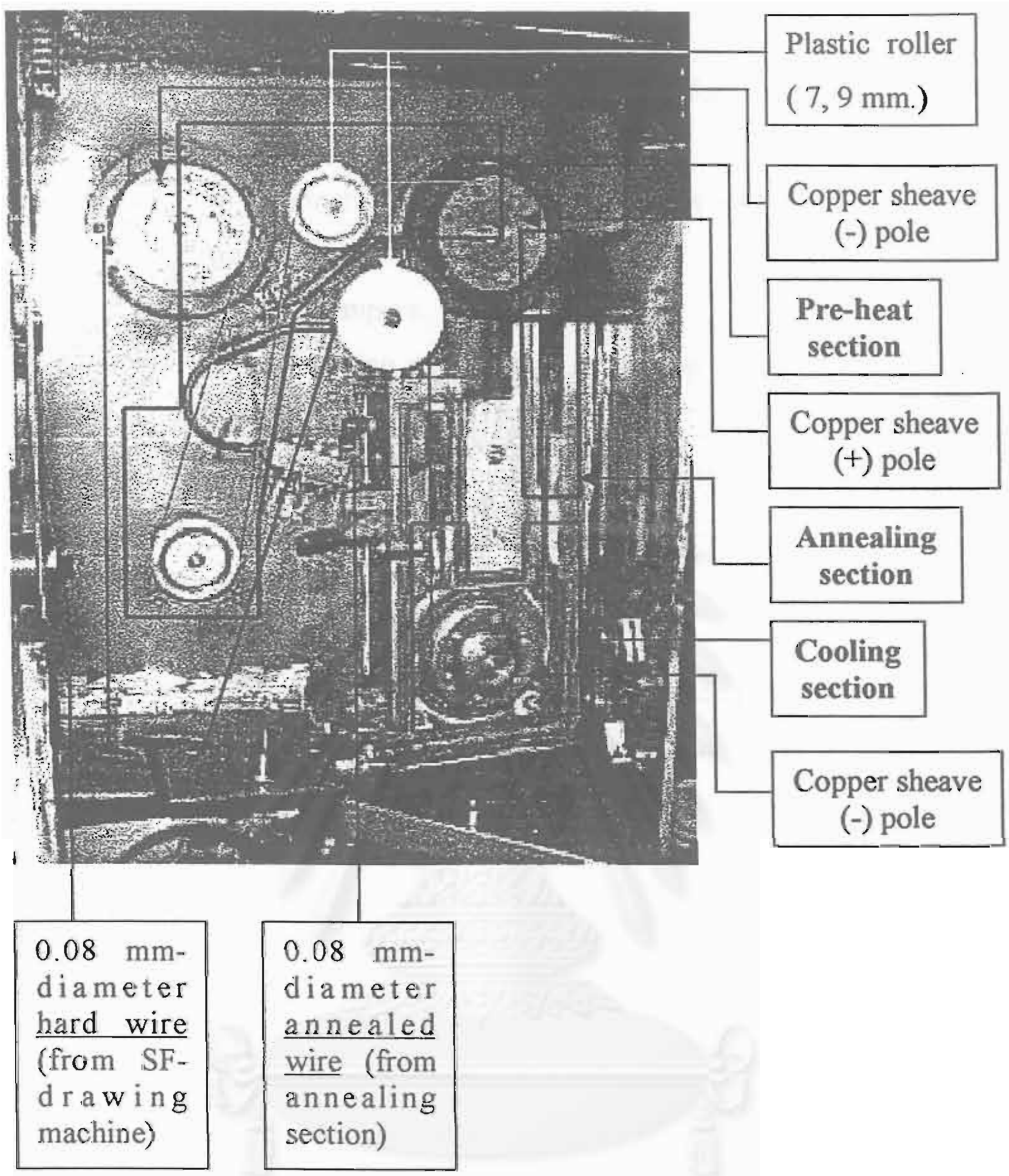


Figure 4.7: Pre-heat, annealing, and cooling section of annealing machine.

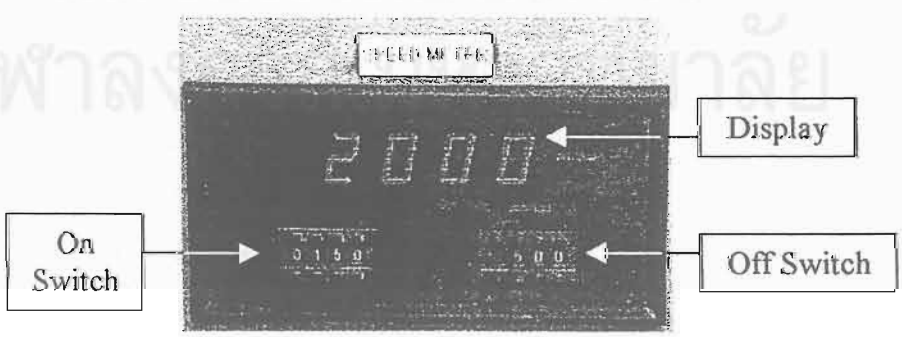


Figure 4.8: Speed metre

3) Electrical control section

- Voltage switch: Adjust the voltage for pre-heat and annealing section.
- Voltage metre: Measure and Display the voltage.
- Ampere metre for annealing section: Measure and Display the annealing ampere.
- Main annealing switch: Turn on/off the electricity for pre-heat and annealing section.
- Emergency switch: Immediately stop the machine.

4) Counter Metre

- Set the length of wire required to produce per bobbin.
- Count/ Display the length of wire produced.
- Slow down the wire speed when the length meet the length set.

5) Speed Metre (See Figure 4.8)

- Display the wire speed.
- Supply the electricity to the wire at the speed set.
- Cut off the electricity supplied to the wire.

6) Cooling section (See Figure 4.7, 4.9, 4.10)

- Turbulent condition during operating
- Length of wire in the cooling section (fixed) 159 mm. (6.26in.)
- Coolant: 1 % concentration of oil in water
    - Flow rates 110 L/min.
    - Temperature set of coolant in tank 60°C
    - Actual temperature in (measured) 50°C (approximately)
    - Actual temperature out (measured) 59-60°C

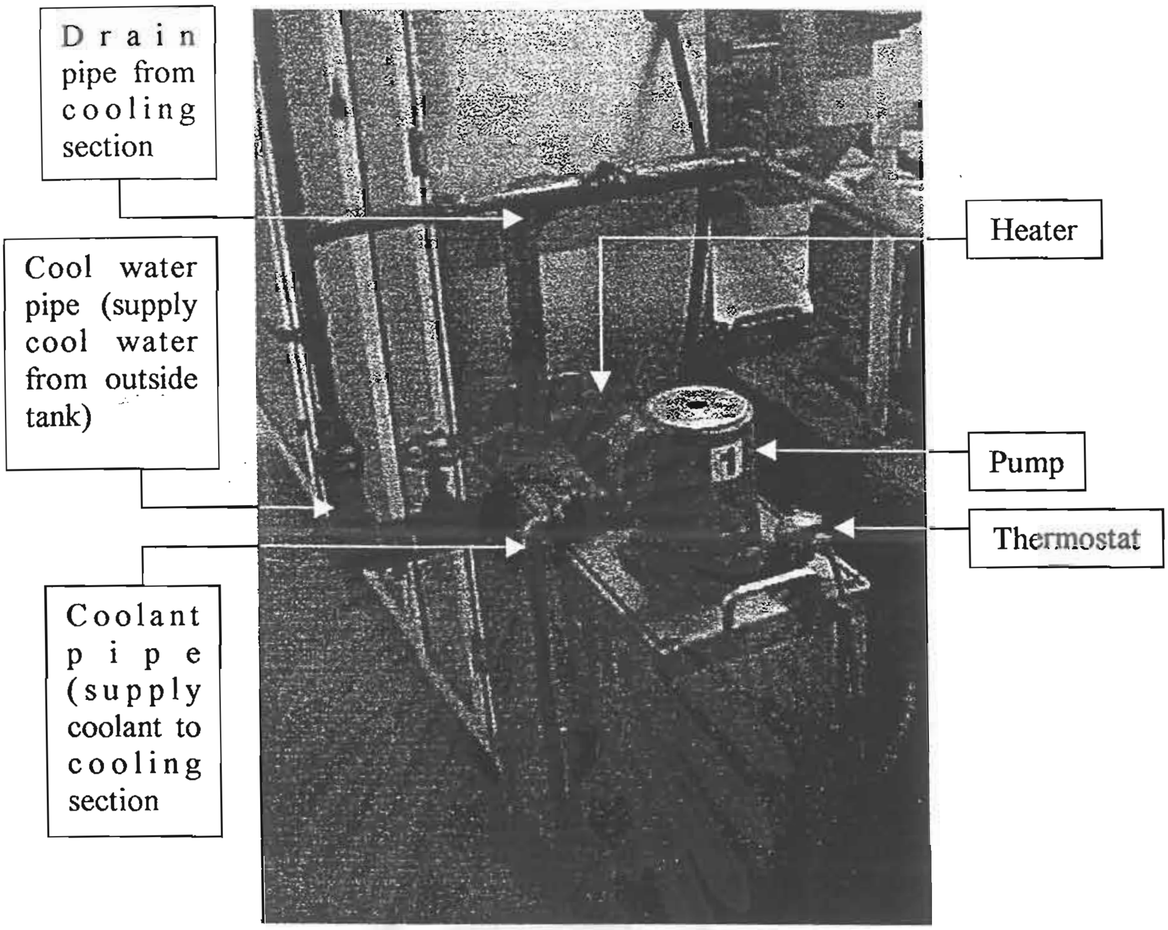


Figure 4.9: Cooling supporting system.

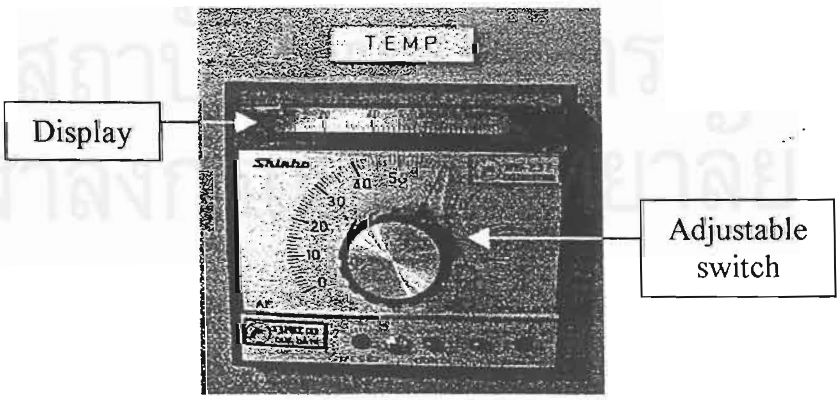


Figure 4.10: Coolant temperature metre and adjusted switch

- Coolant pump: Move coolant from tank to cooling zone.
  - 3-phase electrical oil pump (Brand: Fuji electric)
  - Type: VKP081A (200V, 50Hz, 4heads-2poles)
- Heater: Heating up the coolant temperature.
  - The heater will be automatically turned on if the temperature of coolant in the tank is lower than temperature set.

4.2 Experimental Procedure

As mentioned previously that there are two groups of machine used, the following are the procedure of drawing and annealing.

4.2.1 Drawing Method (See Figure 1.2 in Chapter1)

The drawing process is used to reduce the diameter of wire. The drawing process used is the cold drawing process. Due to the Diagram shown in Figure 4.11, the 8.0mm diameter of soft bare copper rod will be firstly drawn to 2.6mm diameter by the G-class drawing machine. The 2.6mm diameter will be drawn to 0.6mm diameter by F-class drawing machine. Finally, the 0.6mm diameter will be drawn to 0.08mm diameter by SF-class drawing machine. The 2.6, 0.6, and 0.08mm diameter from the drawing machine are called hard wire (hard wire is the wire that is not annealed after the wire is drawn.). The wire is drawn by passing through the dies, which the number of die used for each type of drawing machine are different. The lubricant is necessary during the drawing process. It is used to reduce the friction between dies and wire and reduce the heat occurring as a result of friction.

The drawing method is the same for each drawing process.

1. *Setting the drawing conditions.*
2. *Check the level of lubricant.*
3. *Pass the wire through the dies and roller and then reel the wire end to the bobbin.*

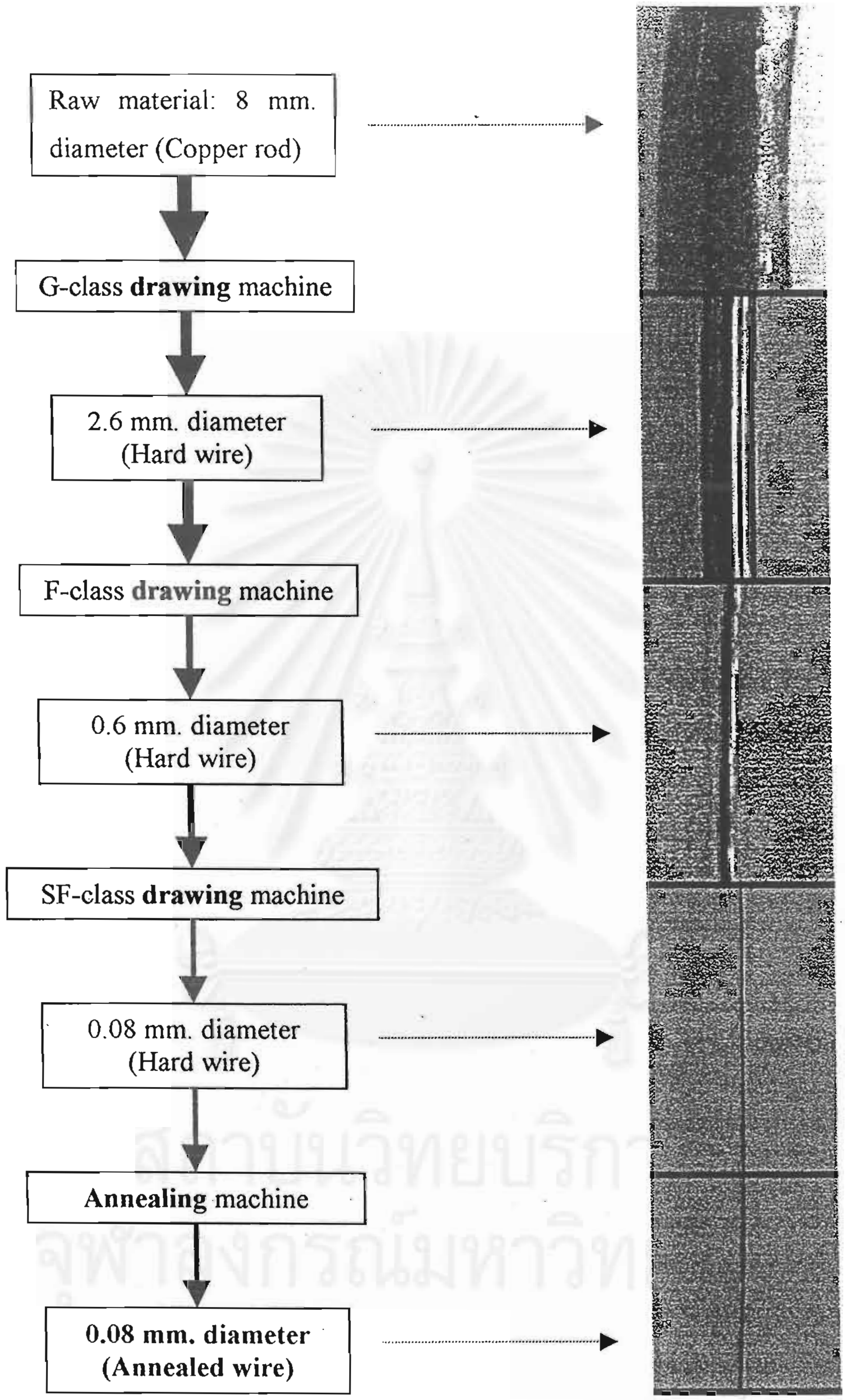


Figure 4.11: Diagram of the process of producing 0.08 mm. diameter (annealed wire) from 8 mm. diameter (soft bare copper rod)

4. *Turn on the lubricant switch and start switch.*
5. *Turn the machine off.*
6. *Change new bobbin instead of finished one.*
7. *Repeat steps one through six for each additional operation.*

4.2.2 Annealing Method (See Figure 4.11)

1. *Setting the annealing machine.*

The conditions of experiment are set as follow.

Variable condition:

- Input voltage
  - 1st experiment 25V.
  - 2nd experiment 27V.
  - 3rd experiment 29V.
  - 4th experiment 31V.
  - 5th experiment 33V.
  - 6th experiment 35V.
  - 7th experiment 37V.
  - 8th experiment 39V.
  - 9th experiment 41V.

Fixed conditions:

- Wire speed 2,000 m/min(1,312in/sec)
- Running length per bobbin 5,000 m.
- Length of wire in pre-heat section 820.42 mm. (32.3in.)
- Length of wire in annealing section 112.78 mm. (4.44in.)
- Length of wire in cooling section 159 mm. (6.26in.)
- Conditions of cooling section are set as normal production.
  - Turbulent condition during operating.
  - Flow rates 110 L/min.
  - Temperature set of coolant in tank 60°C

2. *Check the level of coolant in the tank.*
3. *Pass the hard wire through the copper sheave and plastic rollers and then reel the wire end to the bobbin.*
4. *Turn on the annealing switch and start switch.*
5. *Press emergency switch when the wire length is 5,000 m.*
6. *Change new bobbin instead of finished one.*
7. *Repeat steps one through six for each experiment.*

4.3 Copper Wire Characterisation

4.3.1 Mechanical Characterisation

The mechanical properties of wire were characterised using the tensile testing machine, which was SAIKAWA; with model ET-100 (See Figure 4.12). The testing conditions of percentage of elongation for this study were set the test load of 20 kgf and cross-head speed of 150 mm/min.

- Brand: SAIKAWA
  - Model: ET-100
  - Test type: percentage of Elongation, Strength
  - Load cell (Load detection device) 20 kgf.
  - Cross-head speed 150 mm/min.

Wire from each bobbin was tested to determine the elongation and strength in order to find the change in mechanical properties for each experiment. The procedure of testing was as following.

1. Prepare the samples by cutting the wire at the appropriate length.
2. Setting the machine conditions as follow
   - Set the test method to 'auto'
   - Set cross-head speed (150 mm./min.)
   - Input the diameter of sample wire (0.08 mm.)
3. Ties the prepared wire with upper and lower core of tensile testing machine.

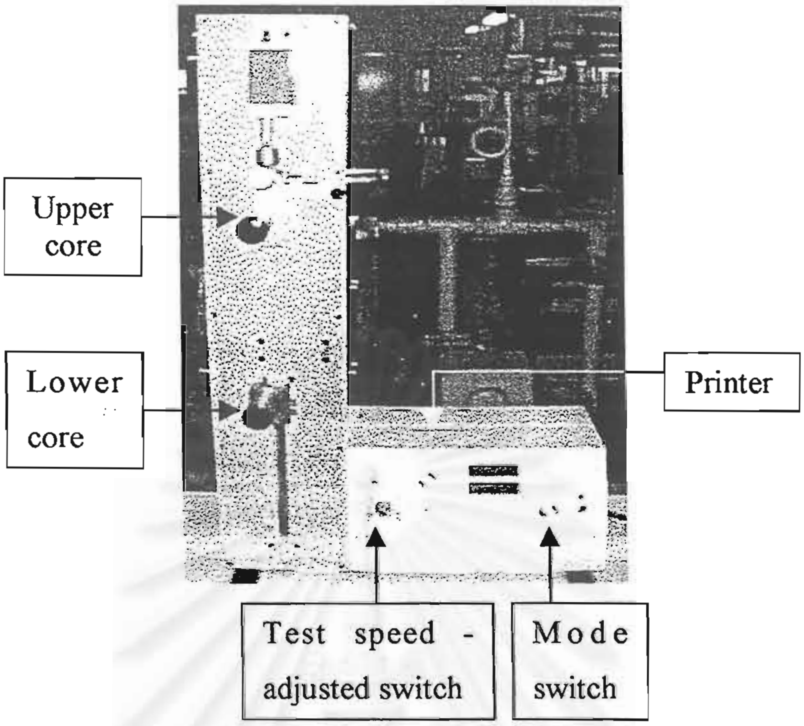


Figure 4.12: Tensile testing machine

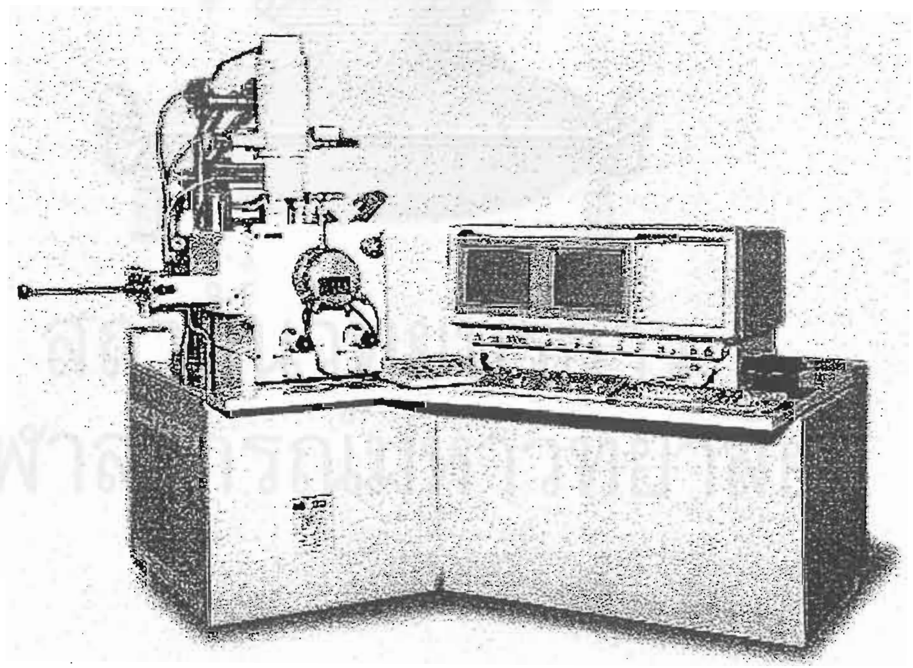


Figure 4.13: Scanning Electron Microscopes (SEM); (JEOL brand: model JSM-6600F)

4. Press the start button.
5. Wait unit wire is broken. (The lower core will move back to the initial position.)
6. Print the test result.
7. Release the breakage wire and repeat steps three to six for additional test.

Since, the average value of percentage of elongation and strength of the sample tested would be used to analyse further, therefore, the number of sample tested per bobbin was 30 samples. Because the average value of sample can represent the average value of population if the number of sample tested are at least 30 samples (refer to page 11 Section7 of "ASM Module handout" University of Warwick 1998 *"Central Limit Theorem (CLT): If the size of sample is sufficiently large (n≥30) then the distribution of the sample means will approximate a Normal distribution, regardless of the actual shape of the populations that the samples were taken from."*).

4.3.2 Microstructure Characterisation

The samples were collected by reeled to bobbin for each experiment and named such as "25 V" means that the samples from the experiment that supplies 25 voltage to the wire. These samples collected would be scanned its microstructure for each experiment by Scanning Electron Microscopes (SEM) (See Figure 4.13), which was JEOL with model JSM-6600F and the specification of this machine is 0.6nm-resolution and x25 to x2,000 (LM mode), x500 to x650,000 for magnification.

The microstructure of the samples tested with varying voltage between 29V –39V was analysed by using Scanning Electron Microscopes (SEM). The method used for SEM was the following steps.

1. Prepare the sample (The preparation procedures are the same for the preparation of both cross-section area and longitudinal area.)
   - Pour the cold resin into the mould that hold the sample wire
   - Bring the solid resin, which contains the sample wire, from the mould
   - Abrasive the solid resin by the abrasive wheel
   - Erode the surface of sample by the acid
   - Coat the sample with gold
2. Insert the sample prepared into Scanning Electron Microscopes (SEM).
3. Adjust the focus until see the clear picture and then take the photo of the copper wire's grain.

4.4 Statistical Analysis Method

The linear regression would be used as an analysis method in order to find the relationship between strength and annealing voltage and percentage of elongation and annealing voltage. The correlation coefficient (r-test) was the approach used to test the significant of the regression relationship and would also be found the confident interval with 95% confidence.

CHAPTER 5

EXPERIMENTAL RESULTS

The experimental results consist of two parts, which were drawing results and annealing results. Both parts were divided into two groups, mechanical properties and microstructures results. The details were following.

5.1 Drawing Results

For the drawing process, the copper wires investigated were 8.0mm, 2.6mm, 0.6mm, and 0.08mm. The 8.0mm diameter was the soft bare copper rod and the others were the hard drawn wires (non-annealed drawn wire). The mechanical properties and microstructure of sample wires were investigated and the results were following.

5.1.1 Mechanical Properties Results

The information involved with the drawing process in term of mechanical properties, which were percentage of cold word, percentage of elongation, and strength, were collected and concluded in the Table 5.1.

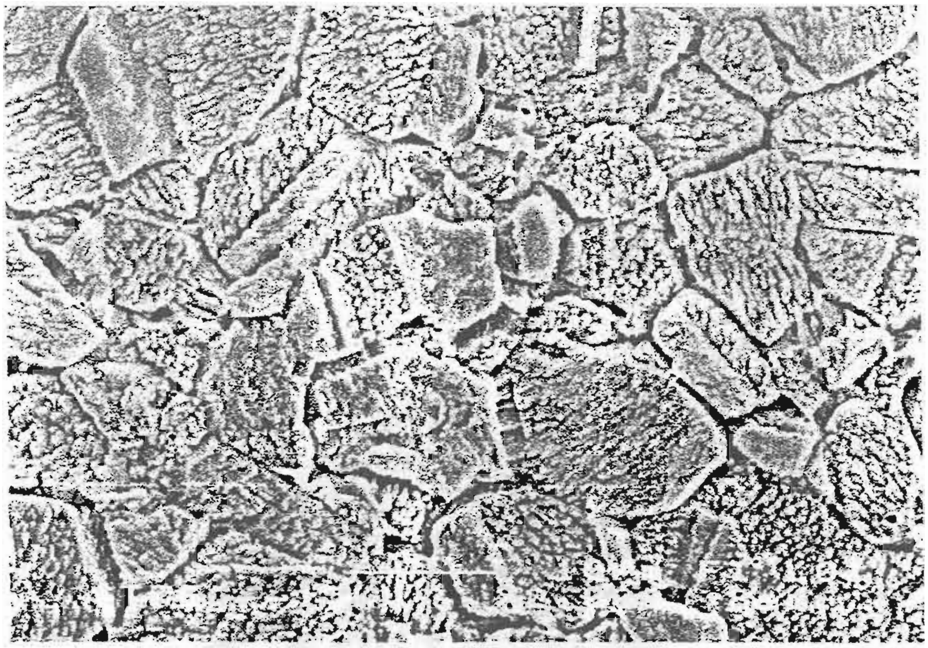
5.1.2 Microstructure Results

The samples were scanned the microstructure in two directions, cross-sectional and longitudinal area. Figure 5.1, 5.2, 5.3, and 5.4 illustrated the microstructure of 8.0mm, 2.6mm, 0.6mm, 0.08mm diameter, respectively.

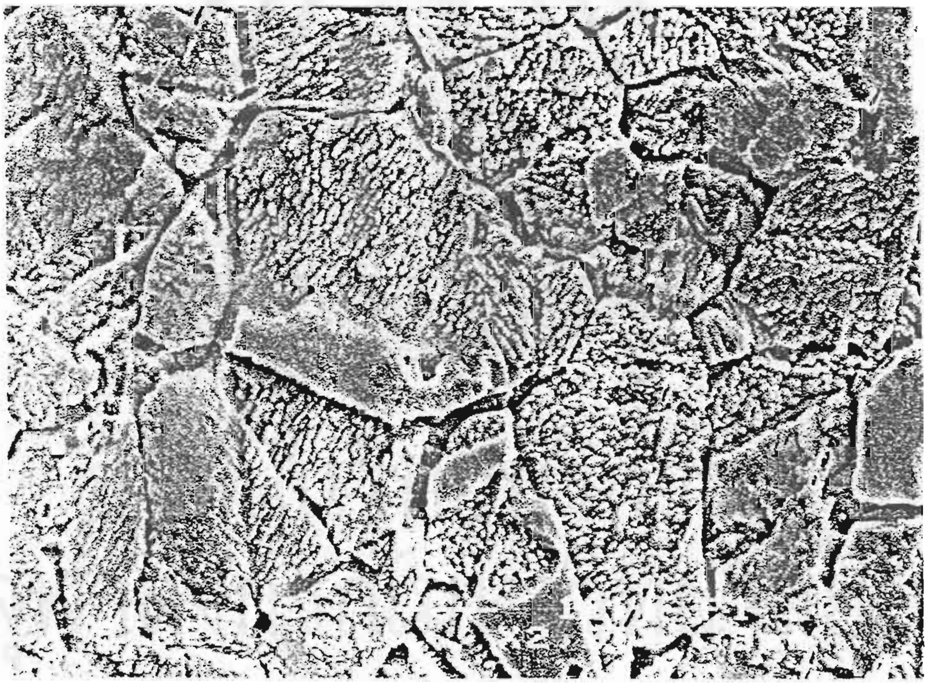
Table 5.1: Mechanical property results of copper before and after cold drawing.

Diameter (mm.)	% Cold Work	Elongation (%)	Standard deviation	Strength (kgf/mm²)	Standard deviation	Note
8.0 (Copper rod)	0.00	41.43	-	24.10	-	Test of supplier
2.6 (Hard wire)	89.44	-	-	-	-	No testing machine available
0.6 (Hard wire)	99.44	-	-	-	-	No testing machine available
0.08 (Hard wire)	99.99	2.40	0.14	33.50	1.52	Data collection

Remark: "*Hard Wire*" is the drawn copper wire without heat treatment.

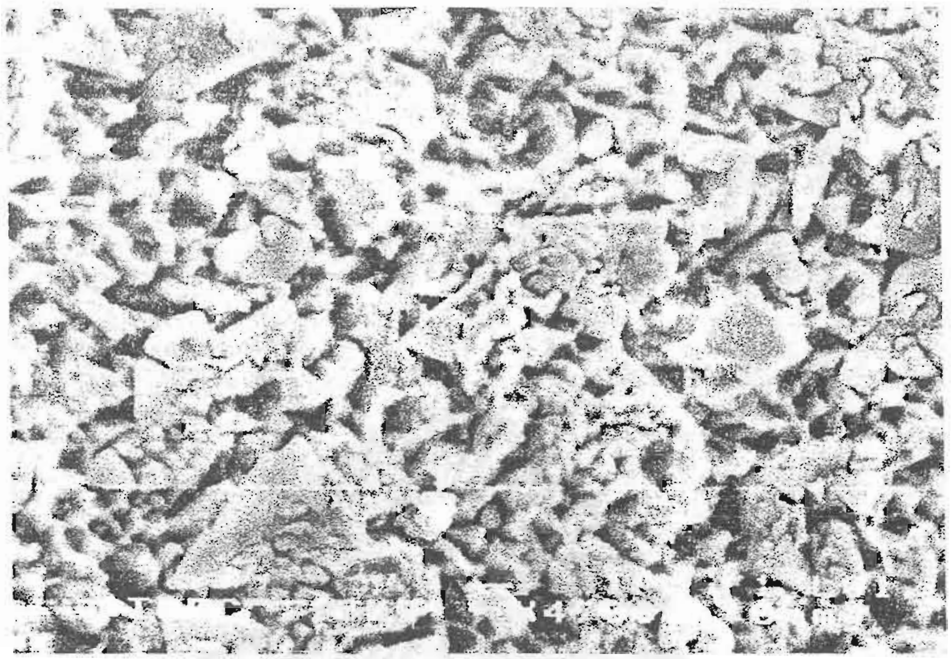


(a): Cross-sectional area

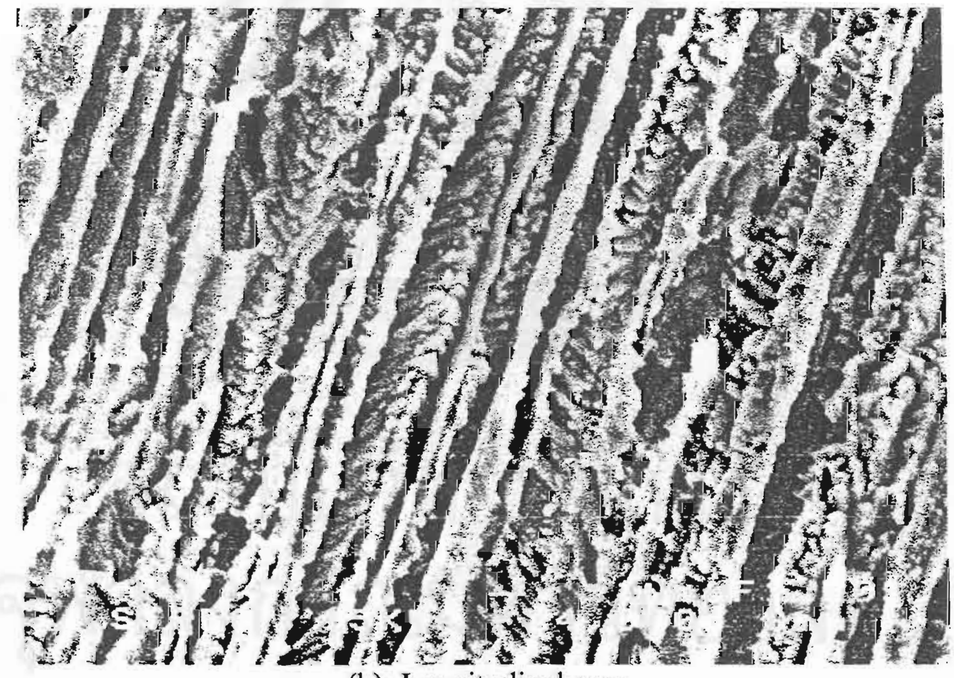


(b): Longitudinal direction

Figure 5.1: SEM of copper rod with the diameter of 8.0 mm before drawing (magnification of 2,000)

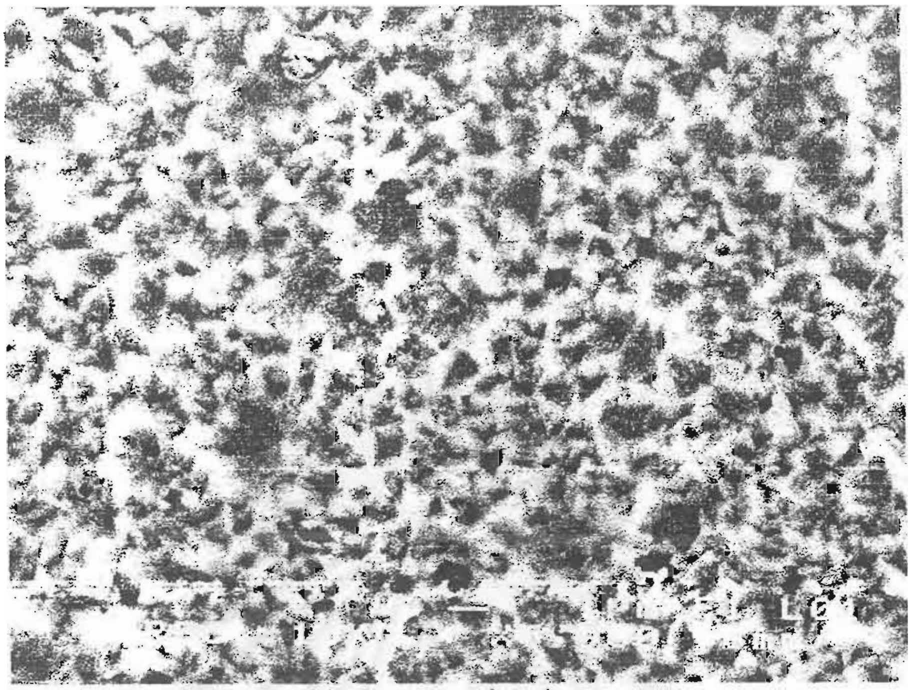


(a): Cross-sectional area

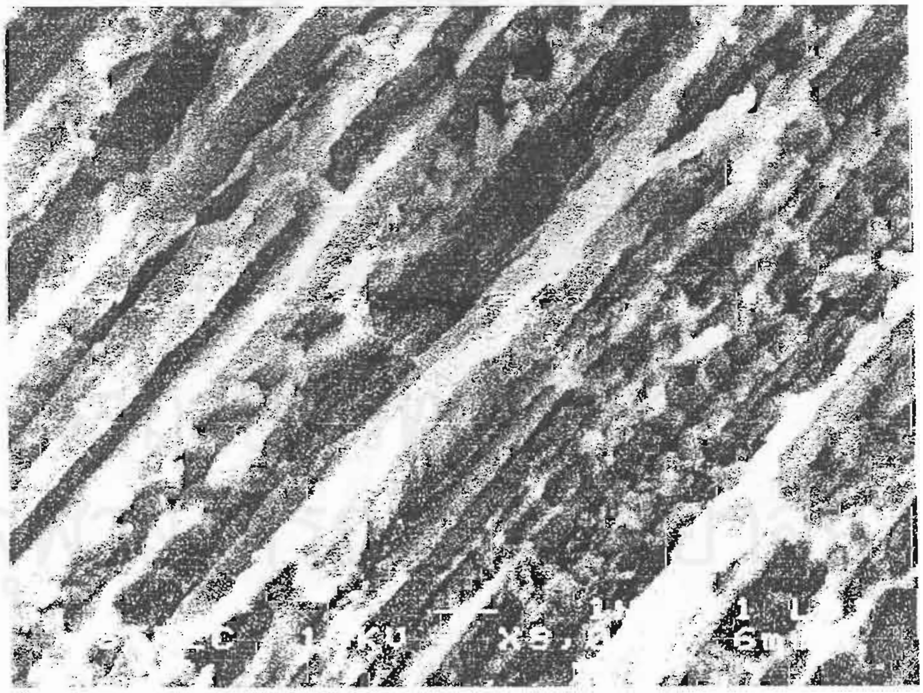


(b): Longitudinal area

Figure 5.2: SEM of copper wire with the diameter of 2.6mm after drawing (magnification of 4,000)

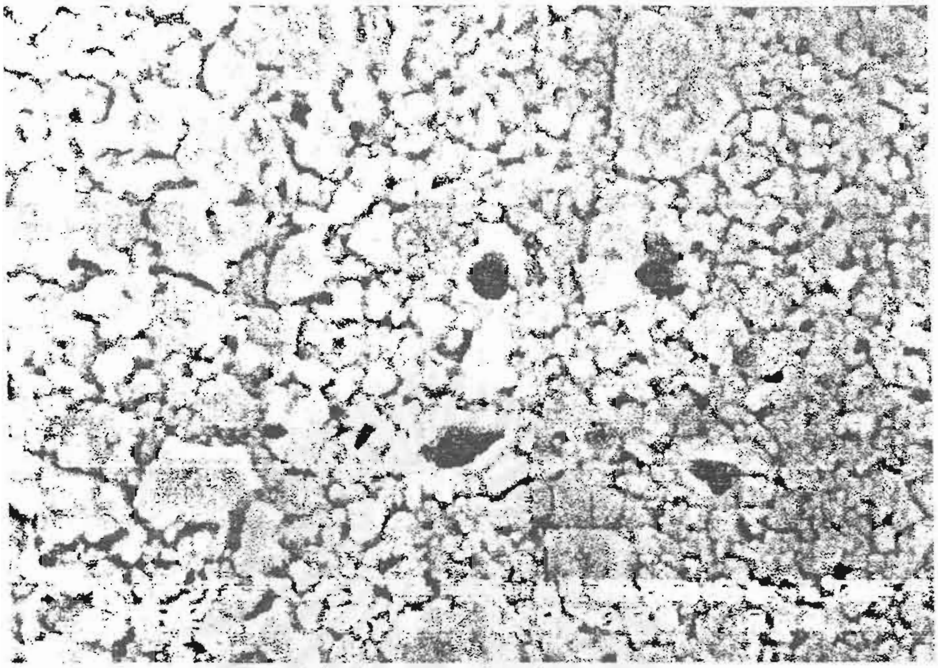


(a): Cross-sectional area

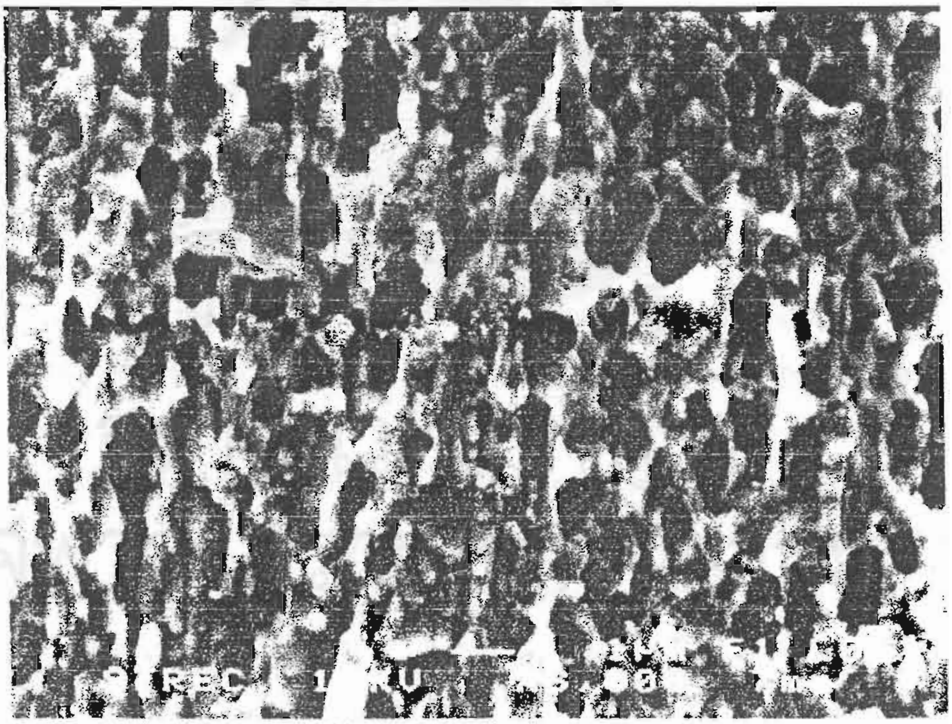


(b): Longitudinal area

Figure 5.3: SEM of copper wire with the diameter of 0.6mm after drawing (magnification of 5,000 and 8,000)



(a): Cross-sectional area



(b): Longitudinal area

Figure 5.4: SEM of copper wire with the diameter of 0.08mm after drawing (magnification of 8,000)

5.2 Annealing Results

The 0.08mm diameter of hard drawn wire was annealed by the annealing machine with the variable in voltage supplied for each experiment. As mentioned in Chapter 4, the voltages supplied were 25V, 27V, 29V, 31V, 33V, 35V, 37V, 39V and 41V. The results of mechanical property and microstructure were illustrated as follow.

5.2.1 Mechanical Properties Results

The samples would be examined the percentage of elongation and strength at each voltage. The average values examined for each experiment were shown in Table 5.2 and these average values could represents the average value of population as mentioned in Chapter4. In addition, the standard deviation of each experiment was also calculated in order to represent the dispersion of each data group.

The annealing temperature and ampere of both pre-heat and annealing were required for the calculation of annealing temperature and related with the voltage supplied to the copper wire, therefore, both pre-heat and annealing ampere at each voltage were collected. (See Table 5.3)

From the Table 5.2, percentage of elongation and strength could be plotted with the voltage supplied. See Figure 5.5, the graph represents the relationship between percentage of elongation, strength and voltage supplied. Graph showed that percentage of elongation increased if the voltage increased from 25V to 39V but it decreased after 39V and strength decreased if the voltage increased from 25V to 33V but it increased from 33V to 39V, however it decreased again after 39V.

Table 5.3 shows the pre-heat and annealing ampere at each voltage supplied of the experiments. The data could be plotted into one graph as shown in Figure 5.6.

Table 5.2: The results of mechanical properties of copper wire after annealing with variation of voltages.

Voltage	Average of %elongation	Standard Deviation of %elongation	Average of strength	Standard Deviation of strength
25	1.43	0.24	35.62	2.73
27	3.34	0.98	31.44	2.78
29	7.94	1.26	30.25	3.36
31	11.95	1.29	30.05	5.82
33	18.21	1.03	24.28	2.26
35	21.43	1.13	27.66	3.17
37	24.10	1.26	27.86	1.62
39*	25.14	1.11	32.64	5.07
41*	24.37	0.78	31.04	1.92

* The drawn copper wires were discoloration.

Table 5.3: The result of current ampere varied with voltage.

Voltage	Pre-heat ampere (A)	Annealing ampere (A)
25	5.6	14.6
27	5.9	15.1
29	6.2	15.8
31	6.5	16.2
33	6.7	16.4
35	7.0	16.7
37	7.2	17.0
39	7.3	17.2
41	7.5	17.4

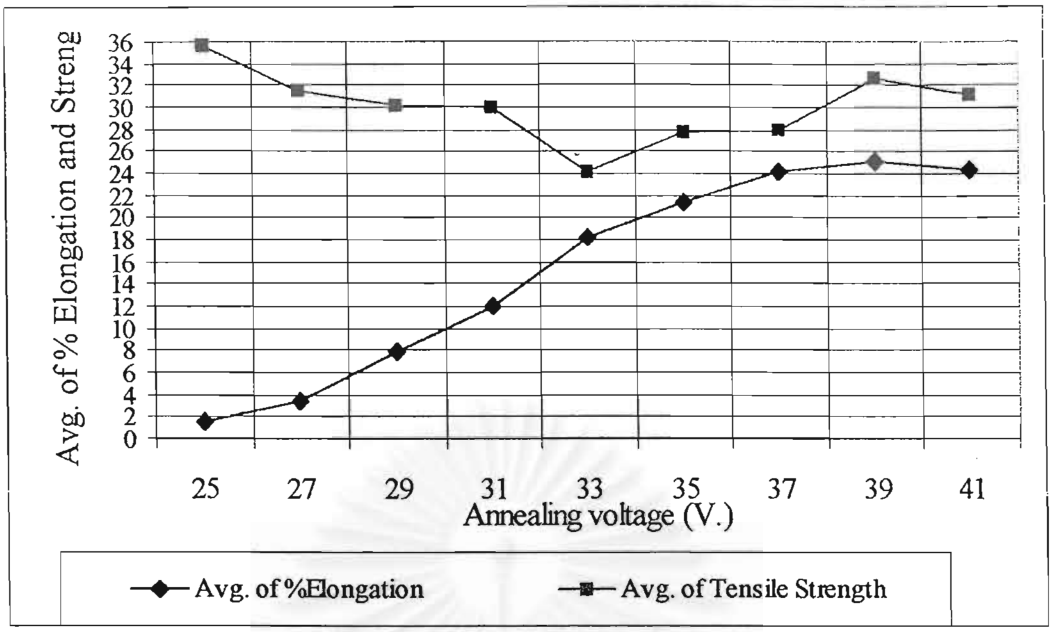


Figure 5.5: The relationship of Average of Percentage of Elongation and Strength versus Annealing voltage of 0.08mm diameter of annealed cooper wire.

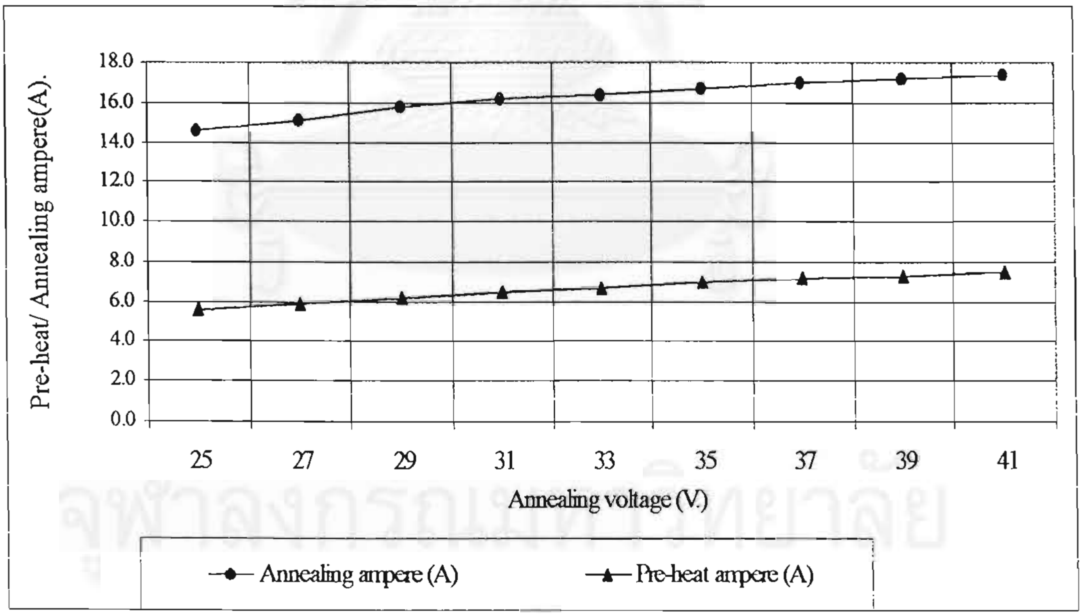
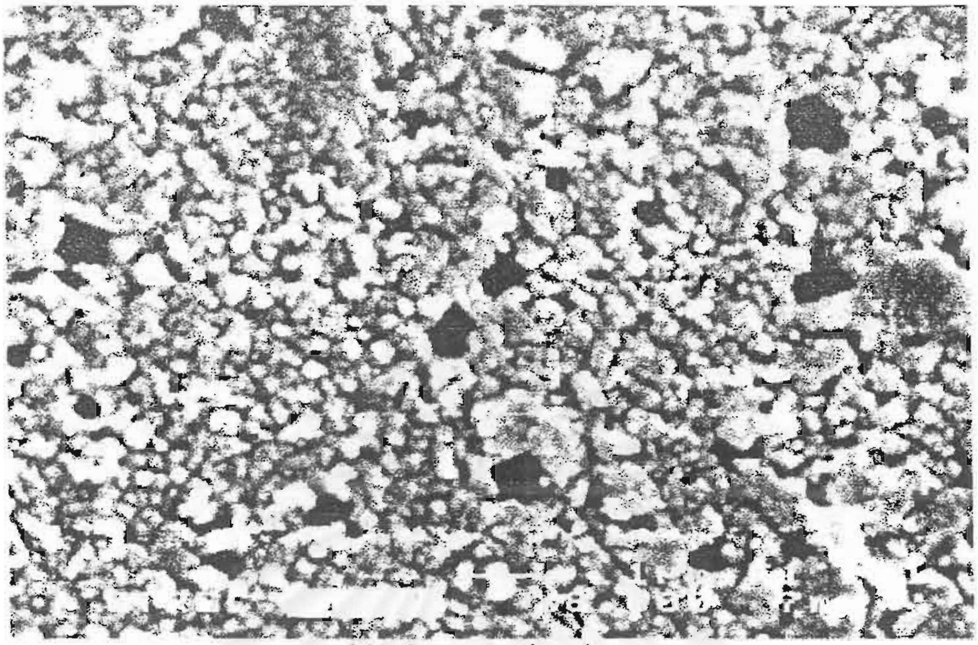


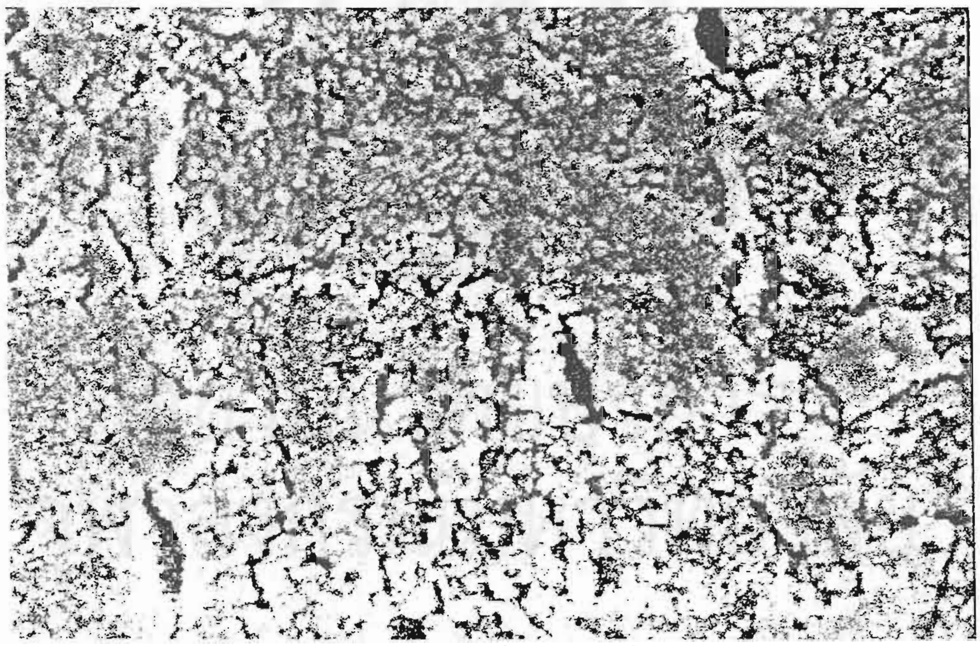
Figure 5.6: The relationship of the Pre-heat and Annealing ampere versus Annealing voltage of 0.08mm diameter of annealed copper wire.

5.2.2 Microstructure Results

The microstructure of samples scanned were the samples from the following experiments, 29V, 31V, 33V, 35V, 37V, and 39V. The samples were scanned in two directions, cross-sectional and longitudinal area. Figure 5.7, 5.8, 5.9, 5.10, 5.11, and 5.12 represent the microstructure of samples respectively.

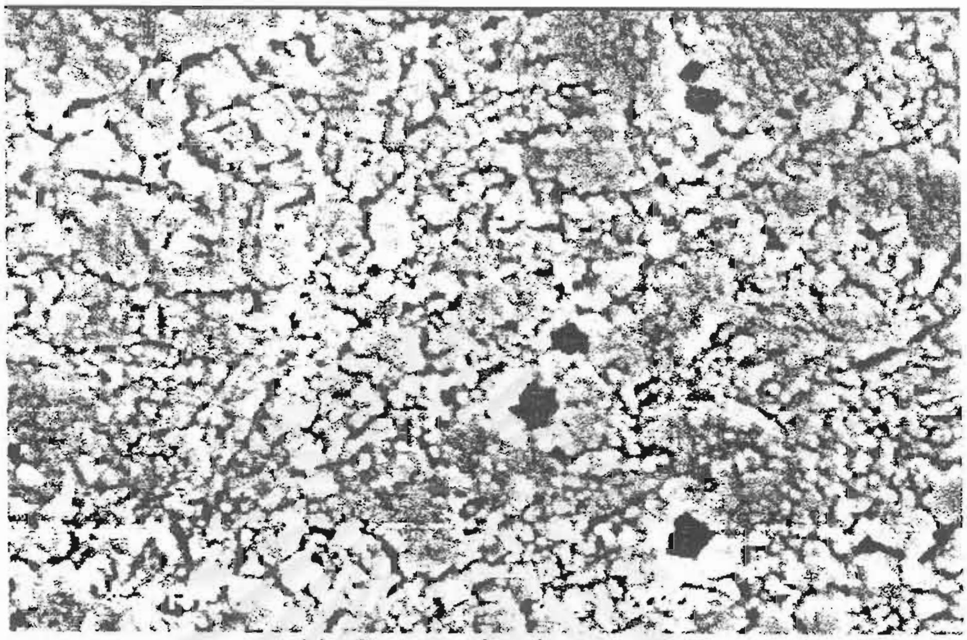


(a): Cross-sectional area

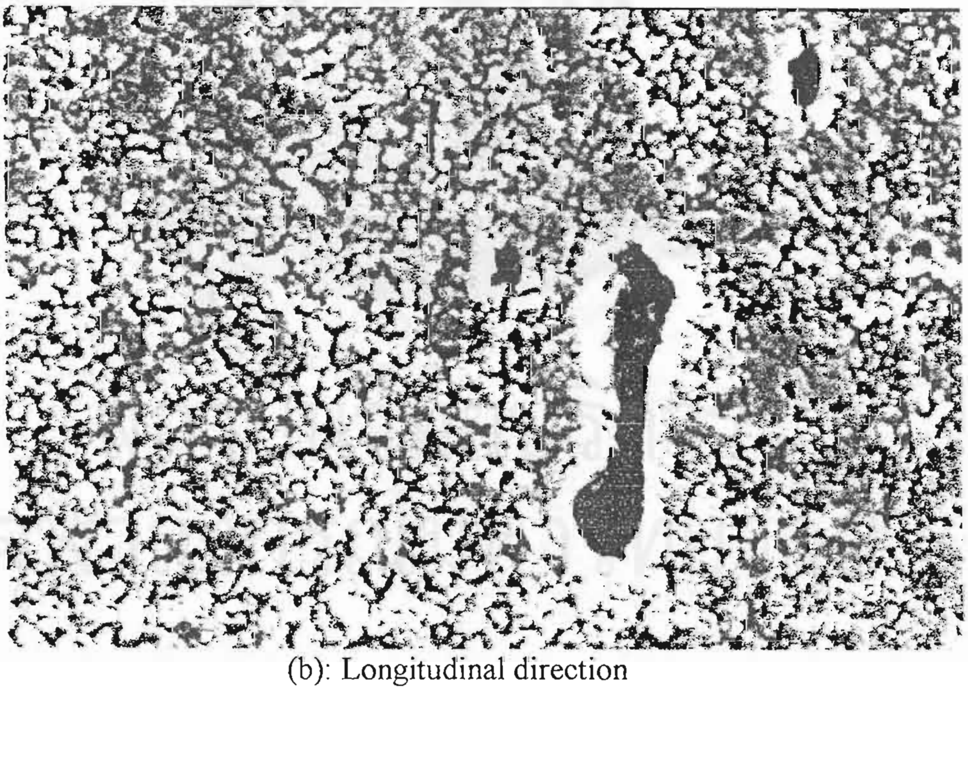


(b): Longitudinal direction

Figure 5.7: SEM of copper wire with the diameter of 0.08 mm after drawing under 29V. (magnification of 8,000)

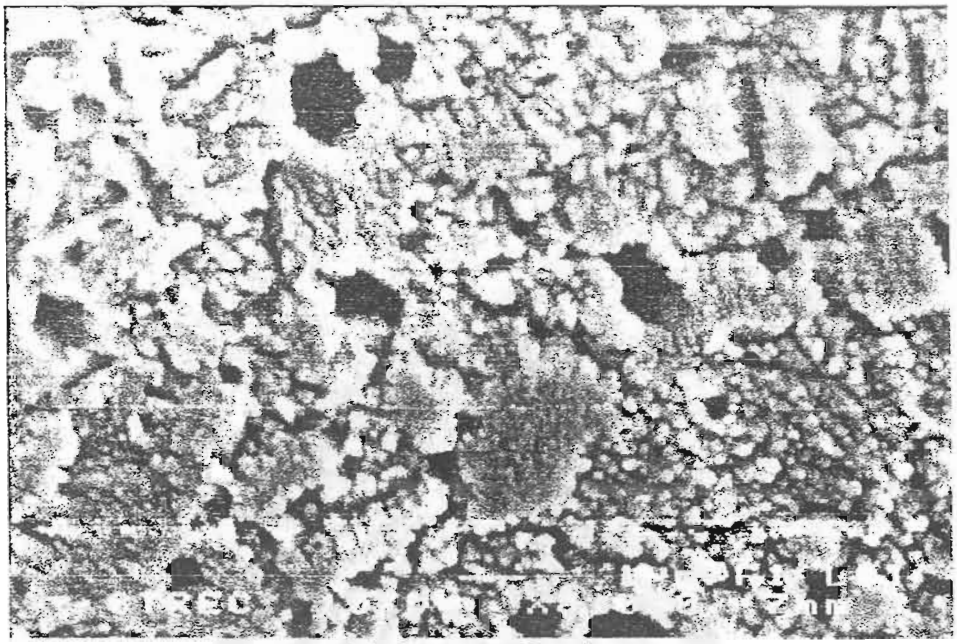


(a): Cross-sectional area

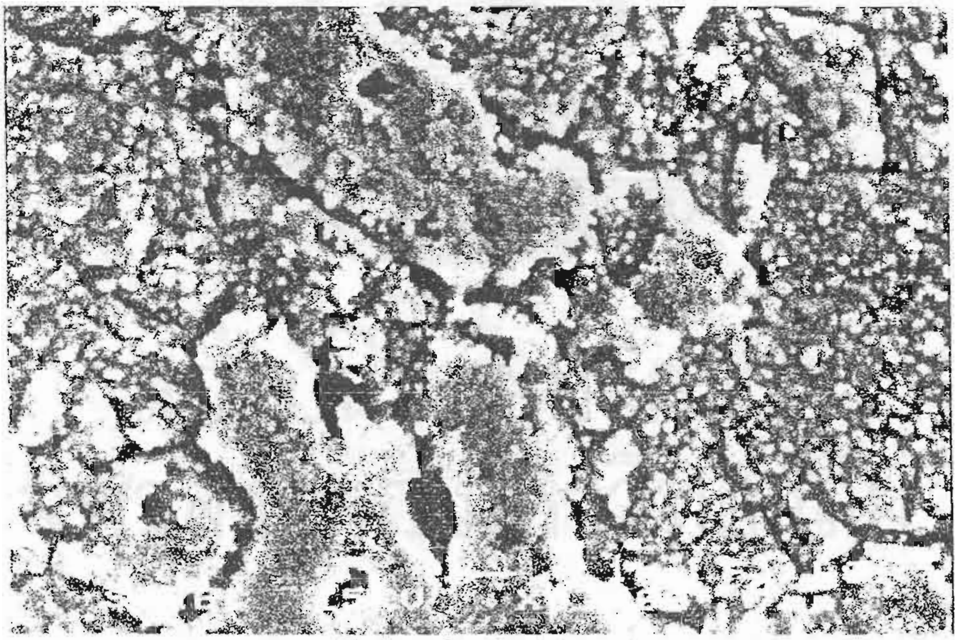


(b): Longitudinal direction

Figure 5.8: SEM of copper wire with the diameter of 0.08 mm after drawing under 31V (magnification of 8,000)

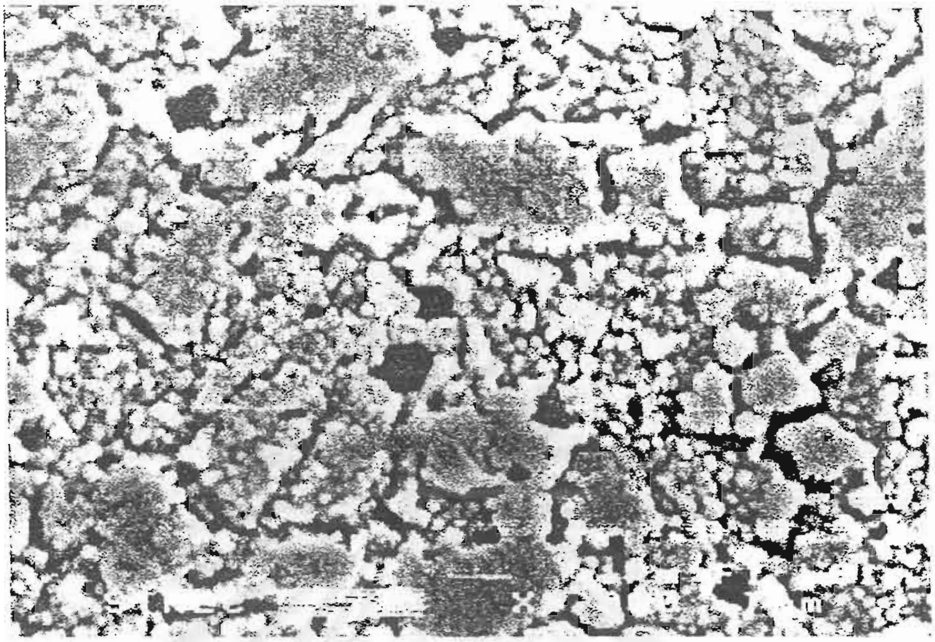


(a): Cross-sectional area

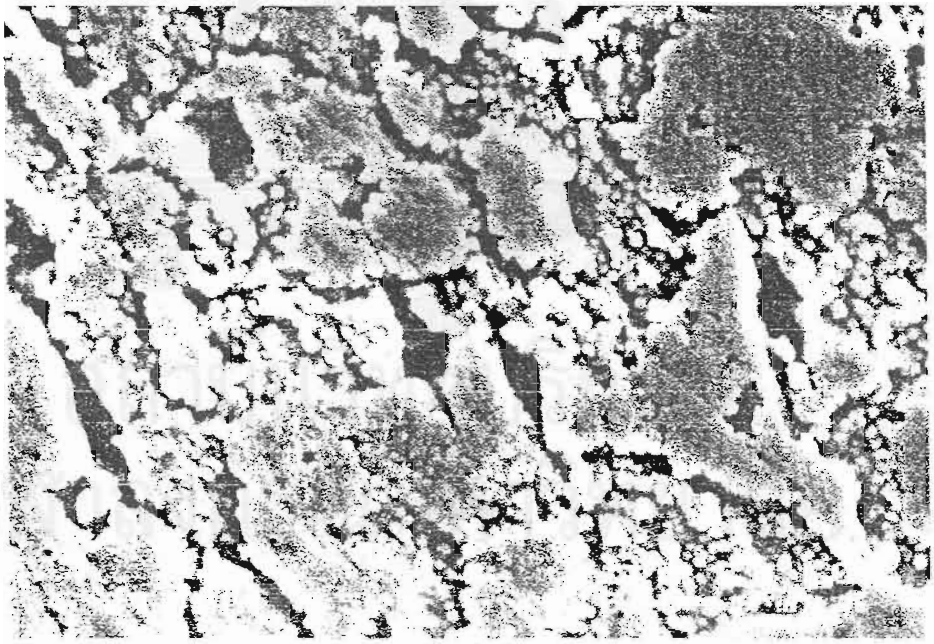


(b): Longitudinal direction

Figure 5.9: SEM of copper wire with the diameter of 0.08 mm after drawing under 33V (magnification of 8,000)

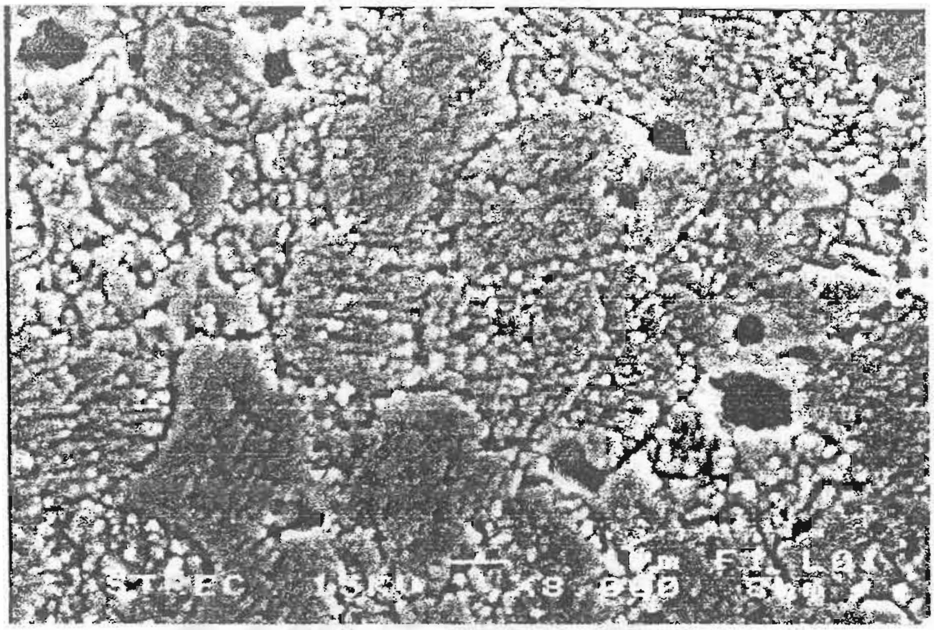


(a): Cross-sectional area

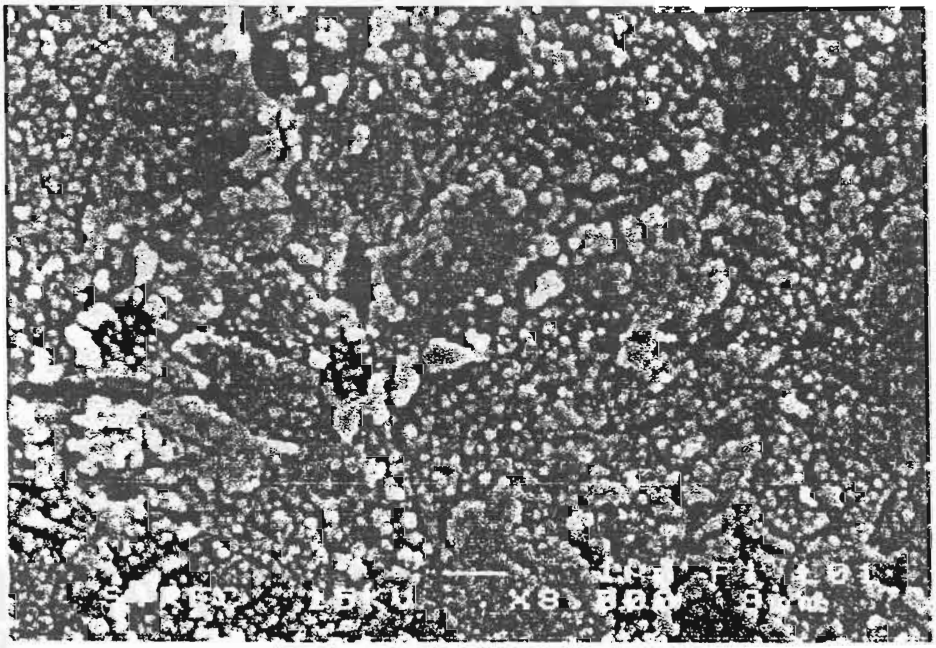


(b): Longitudinal direction

Figure 5.10: SEM of copper wire with the diameter of 0.08 mm after drawing under 35V (magnification of 8,000)

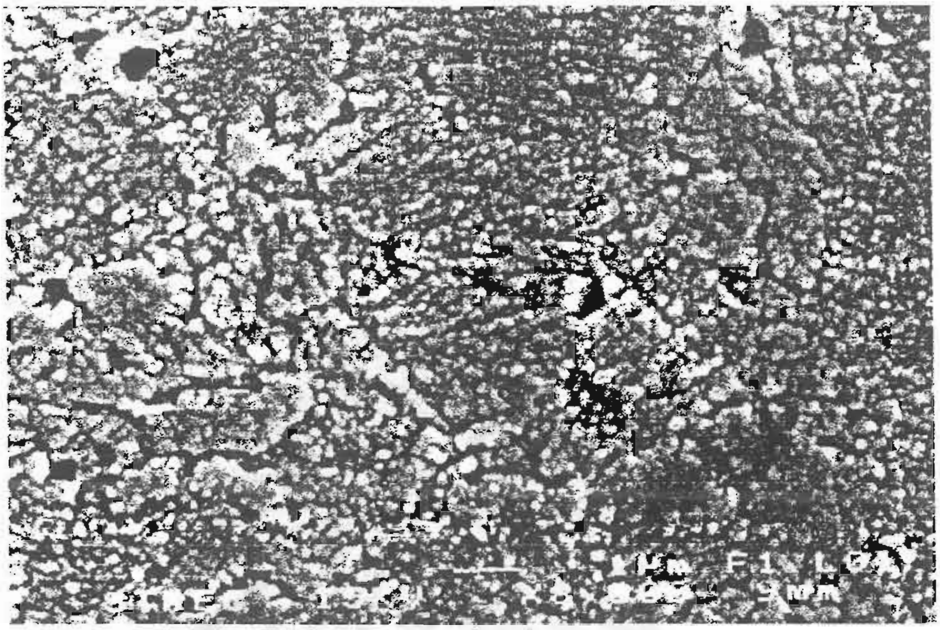


(a): Cross-sectional area

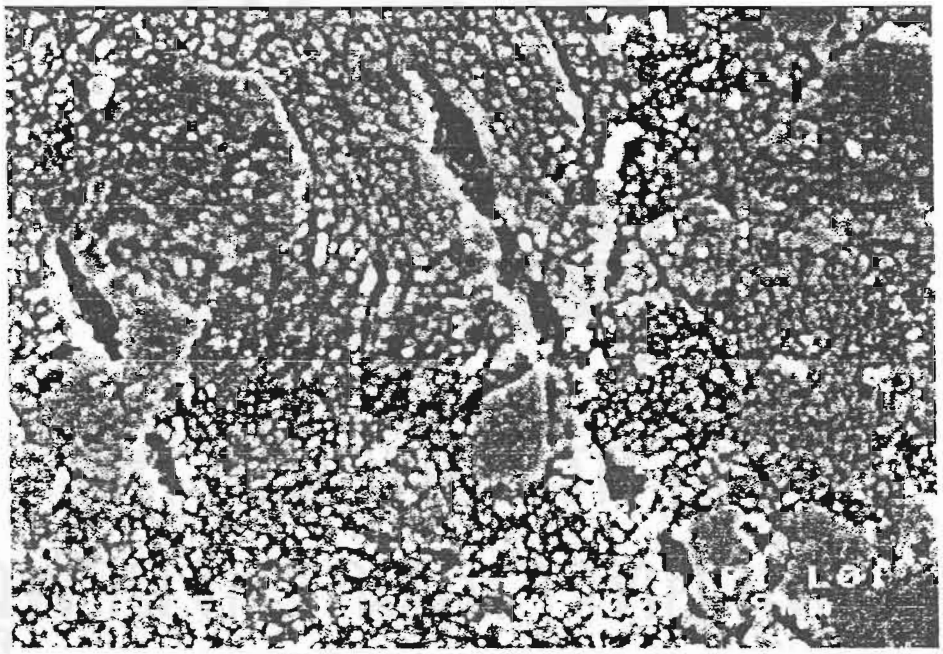


(b): Longitudinal direction

Figure 5.11: SEM of copper wire with the diameter of 0.08 mm after drawing under 37V (magnification of 8,000)



(a): Cross-sectional area



(b): Longitudinal direction

Figure 5.12: SEM of copper wire with the diameter of 0.08 mm after drawing under 39V (magnification of 8,000)

5.3 Statistical Analysis Results

From Table 5.2 and Figure 5.5, the significant of the relationship between strength and annealing voltage and between percentage of elongation and annealing voltage could be tested by the Correlation coefficient (r-test).

Due the graph of strength and annealing voltage, the data at voltage of 33, 39, and 41 should be deleted because of the errors found. The errors were found in term of the porosity at voltage of 33 and discoloration at voltage of 39 and 41. Hence, the new graph for strength and annealing voltage could be plotted as Figure 5.13. For the graph between percentage of elongation and annealing voltage, the discoloration were found at voltage of 39 and 41, it could then be plotted as Figure 5.14.

For the graph between strength (y) and annealing voltage (x), Figure 5.13, showed that the relationship was significant with correlation coefficient (r) of 0.908. The relationship was showed in the following equation.

$$\mathbf{y = 47.97 - 0.57x}$$

From the equation above, the confident interval on the intercept and the slope with 95% confidence was between 36.63 and 59.32, -0.94 and –0.20, respectively.

For the graph between percentage of elongation (y) and annealing voltage (x), Figure 5.14, showed that the relationship was significant with correlation coefficient (r) of 0.993. The relationship was showed in the following equation.

$$\mathbf{y = -50.73 + 2.04x}$$

From the equation above, the confident interval on the intercept and the slope with 95% confidence was between –59.35 and –42.11, 1.77 and 2.32, respectively.

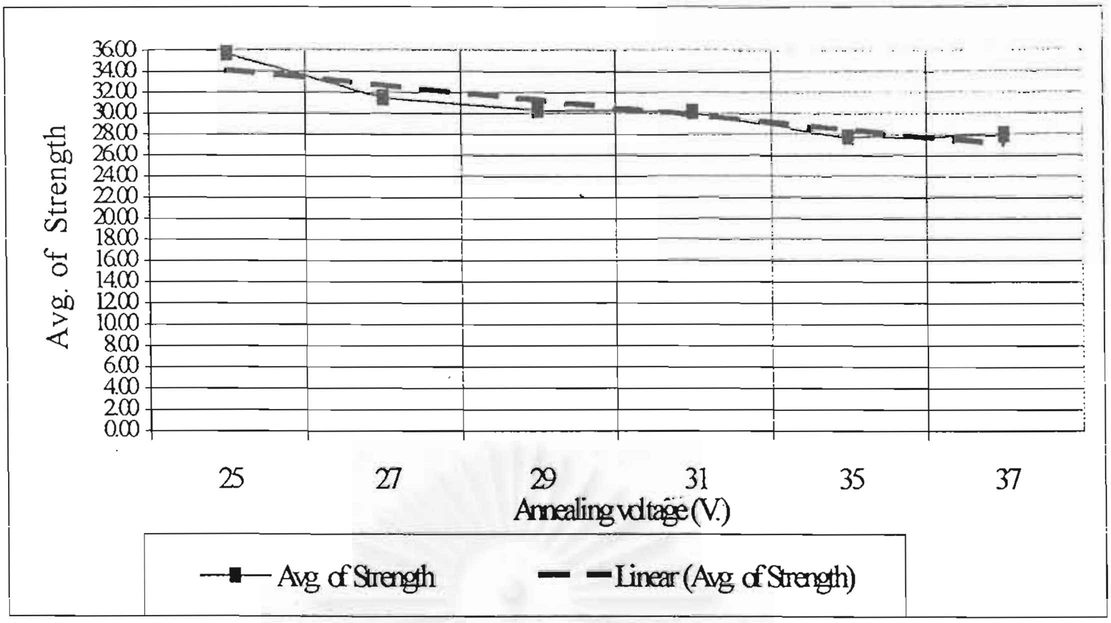


Figure 5.13: The relationship of Average of strength versus Annealing voltage of 0.08mm diameter of annealed copper wire and the regression graph.

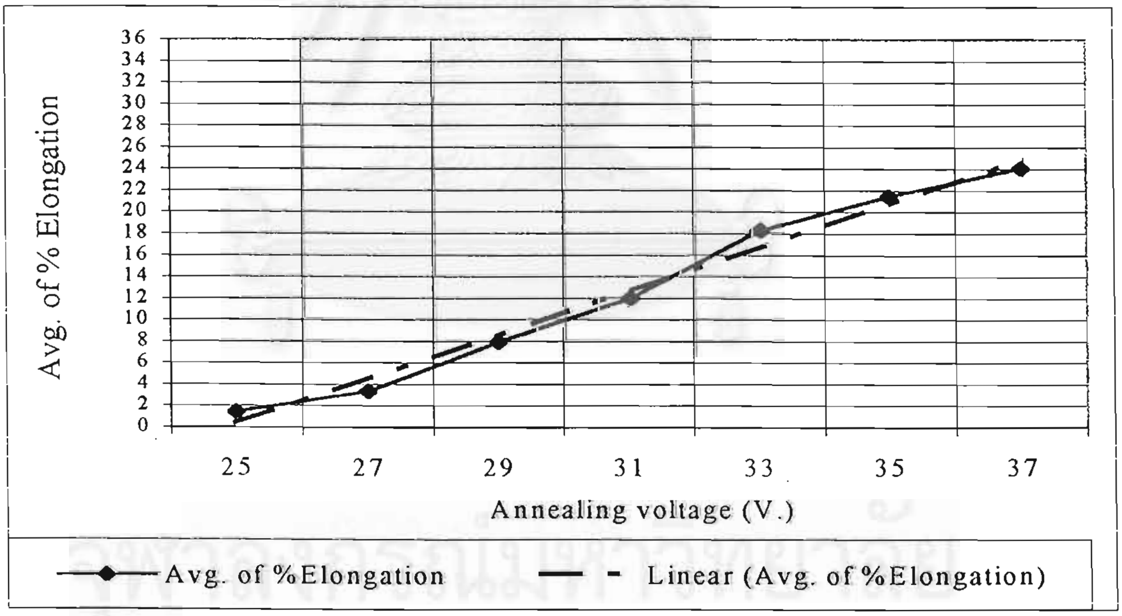


Figure 5.14: The relationship of Average of percentage of elongation versus Annealing voltage of 0.08mm diameter of annealed copper wire and the regression graph.

CHAPTER 6

DISCUSSIONS

6.1 Drawing Process

6.1.1 Mechanical Properties

From Table 5.1 in Chapter 5, 8.0mm diameter of copper rod (its percentage of elongation and strength were 41.43 and 2.40, respectively) was firstly drawn to 2.6mm diameter, which the percentage of cold work was 89.44. The 2.6mm diameter of copper wire was drawn again to the 0.6mm diameter, which the percentage of cold work was 99.44. Finally, the 0.6mm diameter was drawn to 0.08mm diameter, which the percentage of cold work was 99.99, and also the percentage of elongation and strength were 2.4 and 31.25, respectively.

From the result, the percentage of cold work increased with the decreasing of the drawn wire diameter. Comparing between 8.0mm diameter of copper rod and 0.08mm diameter of copper wire that the percentage of cold work was 99.99, the percentage of elongation was vastly decreased, but the strength was increased. Therefore, the higher the percentage of cold work, the greater the tensile strength but lower the percentage of elongation.

6.1.2 Microstructure

Due to the Figure 5.1-5.4, the estimated grain size of each figure was concluded in Table 6.1 and the relationship between Grain size in both directions and percentage of Cold work was shown in Figure 6.1. In cross sectional area, if the percentage of cold work increased, the grain size would be decreased. But, the grain size in the longitudinal direction depended on the amount of cold work that if the high amount of cold work was applied to the wire, the grain would be broken/cracked, therefore, the high amount of cold work shortened the grain size in longitudinal direction.

Table 6.1: Average grain size of copper wire with percentage of cold work.

Diameter (mm.)	% Cold Work	Cross-sectional area (µm.)	Longitudinal direction (µm.)	
			Length	Width
8.0	0.00	6.82	7.50	6.67
2.6	89.44	3.41	23.75	3.00
0.6	99.44	2.09	15.60	1.94
0.08H	99.99	0.89	1.61	1.00

Table 6.2: The change of percentage of elongation and strength of 0.08mm diameter of copper wire.

Voltage	%Elongation	Change	Strength	Change
25	1.43	-	35.62	-
27	3.34	**1.91**	31.44	**-4.18**
29	7.94	**4.60**	30.25	**-1.19**
31	11.95	**4.01**	30.05	**-0.20**
33	18.21	**6.26**	24.28	**-5.77**
35	21.43	**3.22**	27.66	**3.38**
37	24.10	**2.67**	27.86	**0.20**
39*	25.14	**1.04**	32.64	**4.78**
41*	24.37	**-0.77**	31.04	**-1.60**

* The drawn copper wires were discoloration.

Table 6.3: Average grain size of 0.08mm diameter of copper wire.

Voltage supplied	Cross-sectional area (µm.)	Longitudinal direction (µm.)	
		Length	Width
29	0.69	0.70	0.94
31	0.82	0.87	1.07
33	1.44	3.00	1.36
35	1.56	3.90	1.5
37	1.70	2.81	1.67
39	2.08	6.25	2.08

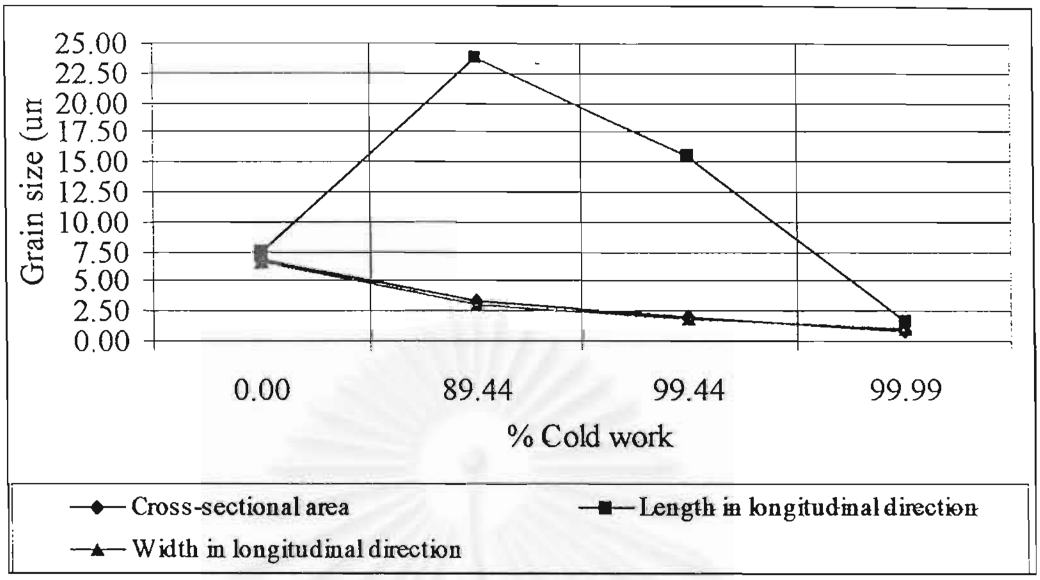


Figure 6.1: The relationship between percentage of Cold work and Grain size in cross sectional area and longitudinal directions.

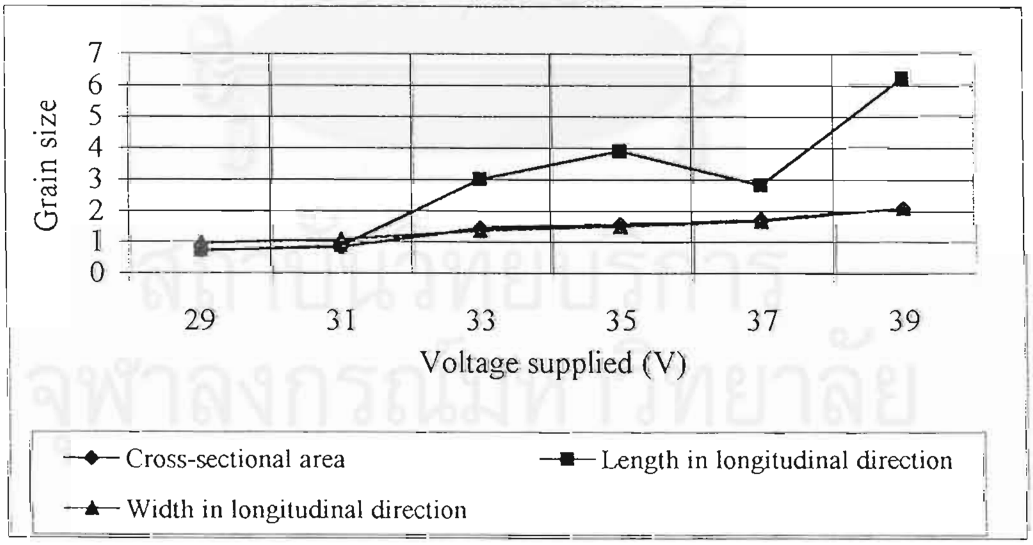


Figure 6.2: The relationship between Voltage supplied and Grain size in cross sectional area and longitudinal directions.

From Figure 5.1-5.4 and Table 6.1, the grain size decreased if the percentage of cold work increased. Therefore, the higher the percentage of cold work, the lower the grain size.

The porosity was mostly found in Figure 5.4 and the porosity found might be the porosity that were the result of high amount of cold work or raw material quality. These could affect the final quality of copper wire in term of mechanical properties.

6.2 Annealing Process

6.2.1 Mechanical Properties

Due to Figure 5.5, the square graph showed the relationship between strength and annealing voltage and the relationships between percentage of elongation and annealing voltage were shown in the trapezoid graph.

For the tensile strength of wire, it was decreased until reach the minimum point at 33V, which was the result of high amount of porosity found, in the range of voltage between 25V and 41V. However, the strength would be increased if the voltage supplied were 39V and 41V, occurred the discoloration.

For the relationship between percentage of elongation and annealing voltage shown in the trapezoid graph, the percentage of elongation increased when the annealing voltage increased in the period of 25V to 39V but the percentage of elongation would be decreased if the annealing voltage applied was over 39V.

Additionally, the increasing of percentage of elongation between 31V and 33V were the highest. The increasing between 27V and 31V were higher than the increasing between 33V and 37V and the increasing between 25V and 27V were the lowest comparing with the previous intervals. The decreasing occurs if the annealing voltage applied was higher than 39V. (See Table 6.2 for the change of percentage of elongation for each experiment)

The highest value of the average of percentage of elongation was 25.14%, which occurred if the annealing voltage applied was 39V. However, there were two major factors for investigating the quality of copper conductor during the production that must be considered, which the first is the percentage of elongation and the second is the discoloration of wire. Due to the experiment, the discoloration occurred if the annealing voltage applied was higher than 37V, therefore, the appropriate highest annealing voltage that could be supplied to the wire without discoloration was 37V, which the average of percentage of elongation at 37V was 24.1%.

6.2.2 Microstructure

From the Figure 5.7 to 5.12, the grain size of each experiment in both cross-sectional area and longitudinal direction were measured and concluded in Table 6.3 and the relationship between Grain size in both directions and Voltage supplied was shown in Figure 6.2. From the table, the grain sizes in cross-sectional area and the length of grain in longitudinal direction increased if the voltage supplied was increased.

The strength of material can be determined by the porosity because they decrease the cross sectional area over which a load is applied. Hence, the strength that material can support was lower when the higher porosity found. Due to the figure 5.9, which was the experiment of 33V, if comparing it with other figures, the porosity was mostly found in Figure 5.9. In addition, the strength measured for the experiment of 33V, shown in Figure 5.5, was the lowest. Hence, the higher the porosity found, the lower the wire strength.

As mentioned previously that the grain size increased if the voltage applied was increased, from Figure 5.5, the largest grain size found at the experiment of 39 V, which had the highest of percentage of elongation in the range of voltage between 29 and 39 (See Table 6.2, 6.3, and Figure 6.2). Therefore, the larger the grain size, the higher the percentage of elongation.

6.2.3 Estimation of Annealed Wire Temperature

Since, the main factor that affects the percentage of elongation was the temperature of wire in the heat treatment process. Hence, the temperature should be concerned. Due to the annealing method used of the factory, the temperature of wire depends on the voltage supplied, which was measured by voltage metre of the annealing machine. However, the wire temperature could not be measured because there was no equipment available. In addition, Frank F. Kraft, Roger N. Wright, and Udayachandran Chakkingal (1991) discussed that *"the peak temperature that the wire reaches in a typical industry annealed not measured"* and Harold Hattersley (1995) advised the calculation method for wire temperature. Therefore, the temperature of wire could only be known by calculation, which the calculation method was mentioned in Chapter 2.

The calculation result of estimated wire temperature in ordinary condition, which the calculation procedure was illustrated in Appendix A, was shown in Table 6.4 and Figure 6.3.

From the calculation result (See Table 6.4), the estimated peak temperature was 1,380°C (2,516°F), which was higher than the melting point of pure copper, which was 1,083°C (1981°F), but the copper wire used included impurities, which increased the melting point, therefore, the melting point of copper wire used was higher than the melting point of pure copper.

The estimated temperature could be either possible or impossible. It could possible, because, the time used for the annealing was only 0.0034sec, furthermore, the time that wire temperature was over the melting point during the annealing process was just 0.0008sec. Therefore, the peak temperature that was higher than the melting point in very short period of time might not affect the copper wire.

Table 6.4: Estimation result of annealed wire temperature in the heat treatment process.

	Length of wire (cm)	Temperature (°C)
Pre-heat	0.00	45.00
Pre-heat	152.40	95.33
Pre-heat	304.80	156.37
Pre-heat	457.20	230.40
Pre-heat	609.60	320.17
Pre-heat	762.00	429.04
Pre-heat	820.42	476.67
Anneal	905.40	1,080.92
Anneal	933.20	1,379.99

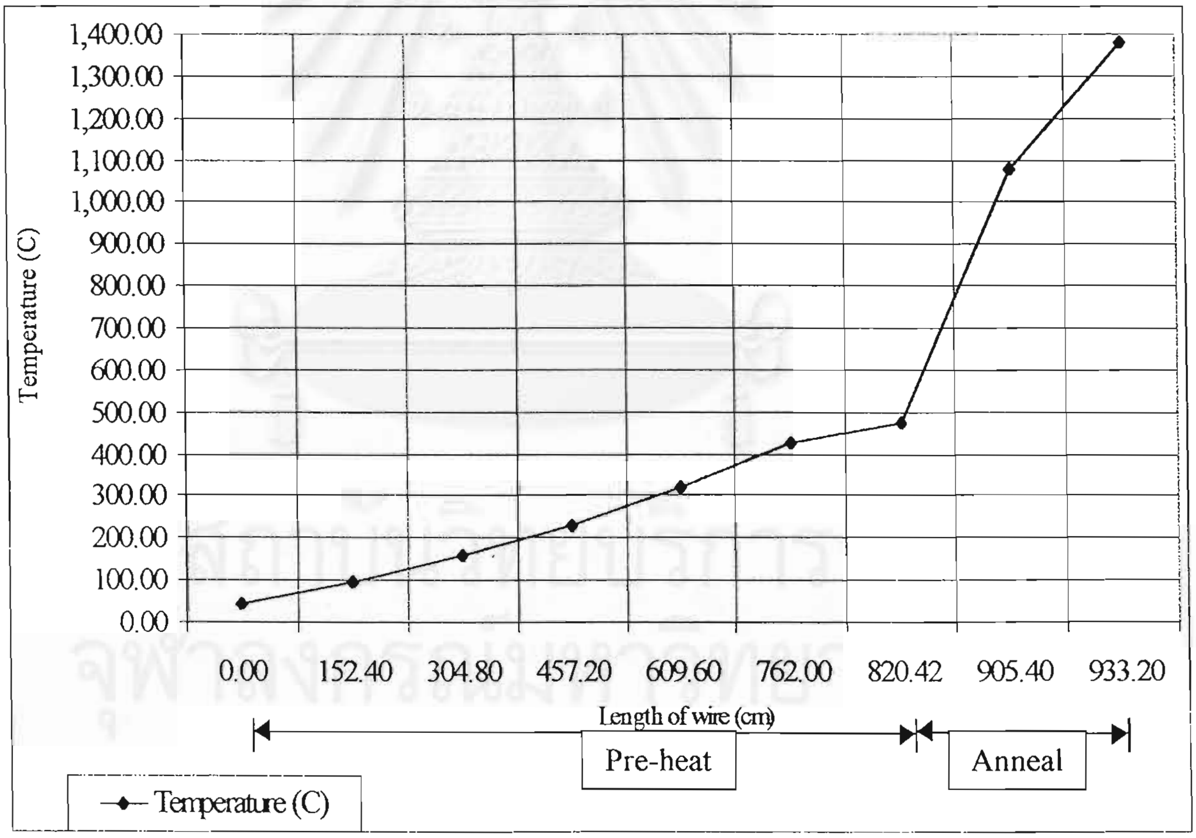


Figure 6.3: The relationship between Annealing temperature and Length of wire.

However, there were many factors required to know for the calculation such as air velocity in the annealing machine, the actual wire speed as a result of slip between wire and sheaves, etc but it was impractical to measure some of these factors in the actual production. Additionally, the formula used was not included the loss in practical production such as the efficiency of carbon brush and annealing sheave ring that affected the result in term of the actual voltage supplied, the actual convection and conduction of wire, etc. Therefore, the result might impossible and the application for more possible result was required.

From the reason mentioned, the result was still the estimated temperature, which was the result of experiment of 33V (existing production condition) and was not exactly accurate and could not completely concluded. Hence, the calculations for other voltages were not conducted.

As mentioned previously, the voltage supplied related with the wire temperature, which should be known in order to represent the relationship between voltage and wire temperature. Therefore, the wire temperature was significant and the calculation of wire temperature might be continuing studied in details for such related factors as the future work.

6.2.4 Cooling Section of the Annealing Process

The temperature of coolant was 50°C approximately. But Harold Hattersley (1995) suggested about the coolant temperature that *"To ensure a reasonable margin of safety, it is generally best to maintain quench temperature between 29.4 and 35°C."* and *" The cooling water temperature is also extremely importance and if it rises above 48.9°C, will usually result in ineffective cooling."*.

The cooling temperature at 50°C was not maintained in the suitable range of cooling temperature. However, this temperature was set as the lowest temperature as possible that the machine could be set because this machine had only the heater to heat up the drain water from cooling section. Therefore, the cooling unit should be applied for this machine in order to maintain the cooling temperature within the range required, which is generally between 29.4 and 35°C.

CHAPTER 7

CONCLUSIONS

The study focused on the annealing process for the drawn fine copper wire, which the type of annealing machine of the factory is the single phase-continuous electrical resistance annealing, 3-sheave type. The study also covered the drawing process, which was the previous process of the annealing process. The mechanical properties and microstructure of copper, 8.0mm, 2.6mm, 0.6mm, 0.08mm(hard wire), and 0.08mm(annealed wire in various voltage) diameter, were investigated.

7.1 Conclusions

After the experimental results were discussed, the conclusion can be drawn as follow.

1. By increasing the percentage of cold work, the strength would be increased, the percentage of elongation and grain size would be decreased.
2. By increasing the voltage supplied to 0.08mm diameter of hard drawn copper wire from 25V to 39V, the percentage of elongation and grain size increased but the percentage of elongation decreased if voltage supplied was higher than 39V (See Figure 2.3, 3.1, and 5.6).
3. The discoloration occurred if the voltage supplied was higher than 37V.
4. The appropriate annealing voltage that could supplied to the wire without discoloration was 37V, which the percentage of elongation at 37V was 24.1%.
5. The estimation of annealed peak temperature of wire at the voltage of 33 was 2,516°F (1,380°C).
6. The large size and high amount of porosity decreased the wire strength, which the lowest strength was 24.28 kgf/mm^2 found at the experiment of 33V, which was mostly found the porosity.
7. The porosity was found in any figures of annealed copper grain. This was the result from high amount of cold work and/or copper rod quality, which should be checked with the supplier.

8. The cooling temperature of the cooling section was too high. Therefore, the cooling unit should be applied for the annealing machine in order to maintain the coolant within the appropriate range, which was between 29.4 and 35°C.

7.2 Further Research

Due to the result in Chapter5 and the discussion in Chapter6 for the estimation of annealed wire temperature, the estimated peak temperature of annealing voltage of 33 was over the melting point of copper. This might be the result from some immeasurable factors used for calculation, which were, for example, the air velocity in the annealing machine, the actual wire speed affected by the slip between wire and sheaves, the efficiency of carbon brush and annealing sheave ring that affected the result in term of the actual voltage supplied, the actual convection and conduction of wire, etc. The temperature estimated might then incorrect.

Therefore, the immeasurable factors mentioned should be studied in details as the further study in order to pursue finding the accurate peak temperature of copper wire in the annealing process without assuming the immeasurable factors.

Due to the cooling temperature discussed in Chapter6 that cooling unit should be applied for the machine, this could be studied further for the properties of copper wire by (1) changing the cooling temperature within the appropriate range, 29.4-35°C. (2) controlling of cooling rate that might also affect/change the properties of copper wire.

REFERENCES

Amstred, B. H., Ostward, E. P., and Begeman, L. M.. (n.d.). *Manufacturing Processes*. 8^{th} ed. (n.p.): John Wiley & Sons.

Brick, R. M., Pense, A. W., Gordon, R.B.. 1977. *Structure and Properties of Engineering Materials*. 4^{th} ed. (n.p.): McGraw-Hill.

David Hallam and Robert Franks. *Practical Aspect of Nonferrous Wire drawing and stranding*, seminar paper.

Donald R. Askeland. 1994. *The Science and Engineering*. 3^{rd} ed. Boston: PWS.

Frank F. Kraft, Roger N. Wright, and Udayachandran Chakkingal. July 1991. The metallurgy of the continuous electrical resistance annealing of copper wire, *Wire Journal International*. 55-60

Frank F. Kraft and Roger N. Wright. (n.d.). *An improved model for the continuous electrical resistance annealing of copper wire*. U.S.A: Rensselaer Polytechnic Institute.

F.F. Kraft, R.N. Wright, and M.K. Jensen. 1996. Kinetics of Nonisothermal Recrystallization. *Journal of Materials Engineering and Performance*. vol. 5(2). 213-219

Groombridge, D.R., Hardman, T.H., and McAllister, P.B.. (n.d.). *Breaks in Drawn Copper Wire*.

Hogg, J.C.. 1990. *Copper Wire Production*. International Wire & Machinery Association. Warwickshire. England.

Horace Pops, and others, 1995. *Nonferrous Wire Handbook*. vol.3. (n.p.): The Wire Association International, Inc.

Http://www.jeol.com. Scanning Electron Microscopes.

John A. S., 1987. *Introduction to Manufacturing Processes*. (n.p.): McGraw-Hill.

Manut Satitjinda. (n.d.). *Metal Forming Processes*. Lecture Sheet. Chulalongkorn University.

Parson, N.C. and Sheppard, T.. September 1988. *Materials Science and Technology*. vol.4. 816-823.

Raymold, A.H.. (n.d.). *The properties of Engineering Materials*. 2^{nd} ed. (n.p.): Edward Amold.

Reverchon, M.. January 1978. *Heat Treatment of Copper and its Alloys* Treatment Technique.

Serope Kalpakjin. (n.d.). *Manufacturing Engineering and Technology*. 3rd ed.. (n.p.): Addison-Wesley Publishing Company.

Sherif D. El Wakil. 1998. *Processes and Design for Manufacturing*. 2nd ed.. (n.p.): PWS publishing company.

S. Ivanov, D. Markovich, L. Stuparevich, and D. Guskovich. 1996. *Effect of degree of cold work and annealing temperature on the microstructure and properties of cold drawn copper wires and tubes*. vol. 19 no.1. University of Belgrade. Technical faculty of Bor, Yugoslavia.

Schey, T.A.. 1970. *Metal Deformation Process*. (n.p.): Marcel Dekker, Inc.

Wickle, K. G.. July 1981. Copper: An Overview of Heat Treat Techniques, *Heat Treating*. 28-34

William F. S.. 1996. *Principles of Materials Science and Engineering*. (n.p.): McGraw-Hill.

Wistreich, J.G.. 1988. *The Fundamentals of Wire Drawing*, Met. Rev. 3 (10), 97-142.

APPENDIX

Calculation Method for Annealing Temperature

$$T = (\sigma_i/\theta)[(e^{(K_2 \times t)}) - 1] + T_i$$

Where: T = Temperature of element after time "t" (°F)

Ti = Initial temperature of wire (°F) = 113°F (45°C)

θ = Temperature coefficient of resistance

= 1.78×10^{-9} Ohm-in./°F

σi = Initial resistivity @ temperature Ti

; σ = σi + θ (T-Ti)

σi = 6.78×10^{-7} Ohm-in. (at 20°C, 68°F)

K_2 = Constant = $(\theta\times K\times I^2)/(C\times\rho\times A^2)$

; K = Conversion factor from electrical energy to heat energy

= 0.0009478 BTU/sec. Watt

I = Current (Referred to experiment of 33V, Table 5.3)

= 6.7 Amp. (Pre-heat leg),

=16.4 Amp. (Anneal leg)

C = Specific heat for copper = 0.092 BTU/ lb.°F

ρ = density of copper = 0.3213 lbs./in.^{3}

A = cross-section area = (¶/4) d^2

= (¶/4) × $(0.00315)^2$

= $7.79*10^{-6}$ in.^{2}(0.005mm.^{2})

t = time = L/V

; L = length of wire between contact sheave and point of interest

= 32.3 in.(820.4mm.);Pre-heat leg,

= 4.44 in.(112.8mm.);Anneal leg

V = Wire velocity

= 1,312.34 in./sec (2,000 m./min)

The estimation of wire temperature at each element after time 't' was following.

					Result	
	t (sec.)	I (Amp.)	L (in.)	L (cm.)	T (°F)	T(°C)
Pre-heat	0.00	6.7	0.00	0.00	**113.00**	**45.00**
Pre-heat	0.0046	6.7	6.00	152.40	**203.60**	**95.33**
Pre-heat	0.0091	6.7	12.00	304.80	**313.47**	**156.37**
Pre-heat	0.0137	6.7	18.00	457.20	**446.72**	**230.40**
Pre-heat	0.0183	6.7	24.00	609.60	**608.31**	**320.17**
Pre-heat	0.0229	6.7	30.00	762.00	**804.28**	**429.04**
Pre-heat	0.0246	6.7	32.30	820.42	**890.01**	**476.67**
Anneal	0.0272	16.4	35.64	905.40	**1,977.65**	**1,080.92**
Anneal	0.0280	16.4	36.74	933.20	**2,515.98**	**1,379.99**

BIOGRAPHY

Mr. Norasit Angkhasirisup was born on August 23, 1997 in Bangkok, Thailand. He got the Bachelor's Degree in Industrial Engineering from Kasetsart University in Academic Year of 1997 and pursued study Master's Degree in Engineering Management at The Region Centre for Manufacturing Systems Engineering, Chulalongkorn University.