

**PHYSICAL AND MATHEMATICAL MODELLING OF WIRE
DRAWING**

Erkan Karaoğlu

A thesis submitted in fulfilment of the requirements for the degree of Doctor of
Philosophy and the Diploma of Imperial College London

2004

ACKNOWLEDGEMENTS

I would like to thank the following people concerned with the laboratory work and the production of this report in that investigation.

Dr. Richard Dashwood and Dr. Henry McShane for their supervision and assistance for that project,

“International Wire and Machinery Association” and sponsoring company “Sarkuysan-İstanbul” and its General Manager Mr. Hayrettin Çaycı for providing financial and material assistance, and their advice on the continuation of the investigation,

Technician Mr. Melvyn Andrews for his help with experimental work at Imperial College,

Erkan Karaoğlu

ABSTRACT

Currently the worldwide production of copper wire exceeds 10 million tonnes per year. The majority of this is produced on continuous, high speed, multi wire production lines. Each wire break causes significant downtimes and hence reductions in productivity. In order to improve the efficiency of such plants an understanding of the origin and physics of wire breaks is required. To this end a study has been conducted on over 4000 industrial wire breaks. Using scanning electron microscopy in combination with EDS techniques the source of the break has been identified and classified as a function of wire diameter and origin of feedstock. It was found that "Inclusion Breaks" and "Macroporosity + V Shape Defect Breaks" were the crucial break types constituting nearly 70% of the breaks examined. It was also found that the origin of the feed stock played a significant role in determining both the origin of the break, and the diameter at which the break occurred.

In order to gain a better understanding of the break determining factors, a validated model of the wire drawing process was developed using the commercial finite element package Forge2. The model was used to study the effect of process parameters during wire drawing such as reduction ratio, friction, die bearing length and reduction angle, allowing the optimum wire drawing conditions to be determined. The model was extended to theoretically investigate the effect of deformable and undeformable inclusion and porosity presence on the wire drawing process.

A drawing stress analysis was carried out for both industrial wire break samples and modelled situations. A critical ratio was determined theoretically and it was confirmed by the data which was extracted from industry. Additionally simulation results confirmed this value. Strain distributions in the wire were also analysed for different materials:

- Defect free
- Containing an undeformable inclusion
- Containing a deformable inclusion
- Containing a pore.

CONTENTS

Chapter 1	Introduction	Page	7
Chapter 2	Literature Review	Page	9
	2.1. History of Copper	Page	9
	2.2. Types of Copper Product	Page	10
	2.2.1. Electrolytic Tough Pitch Copper	Page	10
	2.2.2. Oxygen Free Copper	Page	11
	2.2.3. Phosphorous Deoxidised Copper	Page	11
	2.3. Production Methods for Copper Wire Rods	Page	11
	2.3.1. G.E. Dip-Form Process	Page	12
	2.3.2. Hazelett Process	Page	12
	2.3.3. Properzi System	Page	13
	2.3.4. Outokumpu Process	Page	13
	2.3.5. Southwire Continuous Rod Process	Page	14
	2.4. Cathode Quality and Recommended Specifications	Page	15
	2.4.1. Effect of the Impurity Elements	Page	16
	2.4.1.1. Elements Required Within Certain Limits eg. Oxygen	Page	17
	2.4.1.2. Effects of Undesirable Elements eg. Hydrogen	Page	18
	2.4.1.3. Effect of the Other Impurity Elements	Page	19
	2.5. Rod Classification Tests	Page	20
	2.6. Wire Drawing Process	Page	23
	2.6.1. Copper Wire Drawing Dies	Page	25
	2.6.1.1. Natural Diamond Dies	Page	25

2.6.1.2. Carbide Dies	Page 26
2.6.1.3. Synthetic Diamond Dies	Page 26
2.6.2. Lubrication in Copper Wire Drawing	Page 27
2.7. Theory of Wire Drawing	Page 28
2.7.1. Mechanics of Wire Drawing	Page 29
2.7.1.1. Useful Work	Page 30
2.7.1.2. Friction Work	Page 30
2.7.1.3. Redundant Work	Page 32
2.7.2. Sound Flow vs. Other Patterns	Page 34
2.8. Modelling of Wire Drawing	Page 35
2.8.1. Finite Element Method	Page 37
2.9. Classification of Wire Breaks and Drawability	Page 38
2.9.1. Wire Breaks and Drawability	Page 39
2.9.2. Inclusion Breaks	Page 40
2.9.2.1. Fracture Mechanism	Page 41
2.9.3. Central Burst	Page 43
2.9.4. Checked Wire	Page 44
2.9.5. Macroporosity	Page 45
2.9.6. Tension Break	Page 46
2.9.7. Split End	Page 47
2.9.8. Slivers	Page 48
2.9.9. Weld Breaks	Page 49
Chapter 3 Experimental Procedure	Page 50
3.1. SEM Examination	Page 50
3.2. Experimental Wire Drawing	Page 51
3.3. FEM Model	Page 54
3.3.1. Material Behaviour	Page 55
3.3.2. FEM Model Operation	Page 57

Chapter 4	Experimental Results and Discussion	Page 59
	4.1. SEM Examination of Wire Breaks	Page 59
	4.1.1. Statistical Analysis of Wire Breaks	Page 60
	4.1.2. SEM Studies	Page 65
	4.1.3. Inclusion Breaks	Page 68
	4.1.3.1. Statistical Analysis of Inclusion Breaks	Page 68
	4.1.3.2. EDS and Image Analysis of Inclusion Breaks	Page 71
	4.1.4. Macroporosity Breaks	Page 75
	4.1.5. V Shape Defects	Page 76
	4.1.6. Tension Breaks	Page 77
	4.1.7. Split End	Page 78
	4.1.8. Improper Wire Drawing Practices	Page 80
	4.1.9. Central Burst	Page 80
	4.1.10. Summary of Wire Break Investigation	Page 82
	4.1.11. Drawing Stress Analysis	Page 85
	4.1.11.1. Drawing Stress Analysis of Copper Wire with Deformable Defects	Page 88
	4.1.11.2 Drawing Stress Analysis of Copper Wire with Non-Deformable Defects	Page 92
	4.2. Experimental Modelling Validation	Page 96
	4.2.1. Experimental Wire Drawing Loads	Page 96
	4.2.3. Comparison of the Experimental and Forge2 Predicted Drawing Loads	Page 97
	4.3. Modelling Application	Page 98
	4.3.1 Defect Free Wire(Sensitivity Analysis)	Page 99
	4.3.2 Undeformable Inclusion Wire(Sensitivity Analysis)	Page100
	4.3.3 Undeformable Inclusion(Break Prediction)	Page101
	4.3.4 Deformable Inclusion(Break Prediction)	Page103
	4.3.5 Porosity(Break Prediction)	Page105
Chapter 5	Conclusions	Page107
Chapter 6	Suggestions For Further Work	Page110
	References	Page111

CHAPTER 1

INTRODUCTION

The introduction of multi-line wire drawing machines promises significant benefits in wire production. These machines have become ever more popular due to the advantages they have over single wire machines. Multiwire machines offer the ability to produce a series of virtually identical wires, of identical length, in a convenient form for further bunching and insulating, to produce finished cables. Another advantage is that they take up much less room than the equivalent number of single wire machines. This type of machine draws eight wires simultaneously. However, a break on one line stops production on all eight lines so that, without a many-fold reduction in the incidence of breaks, the benefits of multi-line techniques may be lost.

There are two broad classifications of defect found in copper wire. The first are those introduced during the casting and rolling processes of rod production, and are known as material defects. The second are those introduced at the wire drawing and subsequent processing stages. These are known as wire drawing or processing defects. Identification of the source of wire breaks is an area which is becoming more and more important as international competition for business increases in the wire and cable market.

In the past, small material defects causing wire breaks have not been seen as a serious problem. Nowadays, however, the shift from single wire to multiwire machines has produced new problems. Wire breaks from any cause in multiwire machines can create serious loss of production if they are not kept under control.

Material defects are first detected in the rod making process. Eddy current detectors can find defects near the surface of the rod, and from these results the rod is graded for quality. The rod grading system acts as a selection process, and top grade copper goes for critical processes, such as fine multi-line wire drawing. Although rod selection is carried out when the rod is produced, because only the surface of the rod can be examined, there may still be material defects in the centre of the rod which have gone undetected. These can then show up at some point in the wire drawing process, depending on the size of wire being drawn and the size of the defect.

In this project, the material investigated has the purity level of ETP-Copper (Electrolytic Tough Pitch Copper) which is used broadly in the world copper wire drawing industry. ETP-Copper is used in any field where high electrical conductivity is required (An oxygen content between 0.02%-0.04% as weight).

This research is divided into three main areas. The first part is the investigation of copper wire breaks collected from industry. A classification of wire break types was developed. After classification, inclusion breaks and macroporosity type breaks were determined to be the crucial types and it was decided to focus on these types. A critical defect analysis and modelling of copper wire containing these two type of defects were carried out.

Compression tests were performed to ascertain the rheology of ETP-Cu. The results of modelling were validated against experimental wire drawing trials.

The third part of the project was the simulation stage of wire drawing. Defect free wire, wire with an inclusion, and wire with porosity were modelled. The effects of these defects on wire drawing were investigated. The parameters of reduction ratio, reduction angle of the die, friction condition and bearing length of the die were investigated.

Wire break analysis performed by SEM, and modelling results were compared and correlated.

CHAPTER 2

LITERATURE REVIEW

2.1 History of Copper

Copper was one of the very first metals known to mankind and was used in many different ways. In the beginning it was a useful metal for everyday necessities, for various weapons, axes, daggers and spears etc. It was then found that it was easy to shape without melting and casting. The metal began to be used for a wide range of items including belts, Maltese crosses, needles, jewellery, trumpets, kettles and doors. [1,2,3]

Nowadays, the use of copper throughout the world can be divided, approximately to the following areas:

[3]

Approximately 50%	In the electrical and electronic industries (conductors for electricity and heat)
Approximately 15%	In the building industry (pipes for gas and water, fittings, valves and controls)
Approximately 15%	In general industry (process components, sockets, welding equipment, bearings, cast components)
Approximately 12%	In the transport industry (car industry)
Approximately 8%	Miscellaneous

The importance of copper has increased dramatically worldwide: [3]

In 1700	9 000 tons produced
1966	5 310 000 tons produced
1973	9 000 000 tons produced
1980	9 500 000 tons produced
1987	10 000 000 tons produced
1995	15 000 000 tons produced
2003	20 000 000 tons produced

The conventional operation for manufacturing raw copper called Blister copper, comprises preparatory calcination, melting and converting. Blister copper, which contains approximately 98% copper, is refined electrolytically to electro copper, which contains at least 99.995% copper.

Anode copper is produced from blister copper with the addition of a small quantity of copper scrap by fire refining in refining furnaces at 1250°C. The copper content of the anode is 99.5% minimum. Copper anodes from the anode casting are transformed into copper cathodes by an electrochemical method in which pure copper, dissolving from the anode, is deposited on the starting sheets producing copper cathodes with a 99.99% copper content.

The outstanding conductivity of copper for heat and electricity combined with good workability makes the metal and its alloys among the most important in the industrial world. Copper can be cast into almost any form. It can also be rolled, pressed and drawn. The last three processes are possible cold or hot. [3,4,5]

2.2 Types of Copper Product

The major products from the melting of electrolytically refined cathodes are electrolytic tough pitch (ETP) copper, which accounts for 80% of the total, oxygen-free copper and phosphorus deoxidised copper. [1,2,4]

2.2.1 Electrolytic Tough Pitch (ETP) Copper

Electrolytic copper is melted, controlling the oxygen content in the range of 0.02%-0.04%, to produce tough pitch copper. The oxygen in tough pitch copper has a beneficial effect on electrical conductivity. Above about 0.01% it causes Fe, Pb and Sn to precipitate as oxides from solid copper and it thereby removes the deleterious effects which these impurities have on electrical conductivity. [1,2,4,6]

ETP copper can be used in any field where high electrical conductivity is required; electric cables, energy transfer and telephone lines, railway electrification, motors-generators-transformers electrical windings, energy bus bars, contacts, various segments of radios and televisions, switches, terminals, commutators, heat exchangers, car radiators, equipment for food industry, housing, kitchen utensils, etc.

2.2.2 Oxygen-Free Copper

Where the high electrical conductivity of ETP-Cu and the weldability of phosphorous deoxidised copper are both required, the oxygen is removed by performing the melting and casting in the presence of carbon and reducing gases. Oxygen-free copper ($<0.001\%$ Oxygen) is used for specialised applications, e.g. finely drawn wire and electronic components, and thus constitutes a few percent of the market. [1,2,4,7,8]

2.2.3 Phosphorous Deoxidised Copper

ETP-Cu is difficult to weld because hydrogen in the welding flame reacts with the oxygen of the copper to form steam bubbles in the weld. The resulting porosity substantially weakens the joint. This condition is avoided by adding phosphorous to the copper just prior to casting (usually 90% Cu, 10% P alloy). [1,2,4]

2.3 Production Methods for Copper Wire Rods

Copper rod is the raw material for various types of copper wire products such as building wire, telecom cable, power cable, automotive wire, etc. Some of the products are very demanding regarding the rod quality. Others can use lower quality rod as raw material. [1,5,7]

Generally, the production methods for copper rods can be divided into five main categories; [1,4,5]

1. General Electric Dip-Form Process
2. Outokumpu Process (Upcast Method)
3. Hazelett Process (Contirod)
4. Properzi System
5. Southwire Continuous Rod System (SCR)

In this chapter, particular attention is paid to the SCR and Outokumpu Processes. The wire breaks, investigated during this project, originated from these two processes.

In Figure 2.1., the capacity distribution of copper rod production methods can be seen, with Southwire accounting for nearly half and Contirod for over a quarter. The other Continuous Copper (CC) rod technologies each account for around 5-6% of the total. [9]

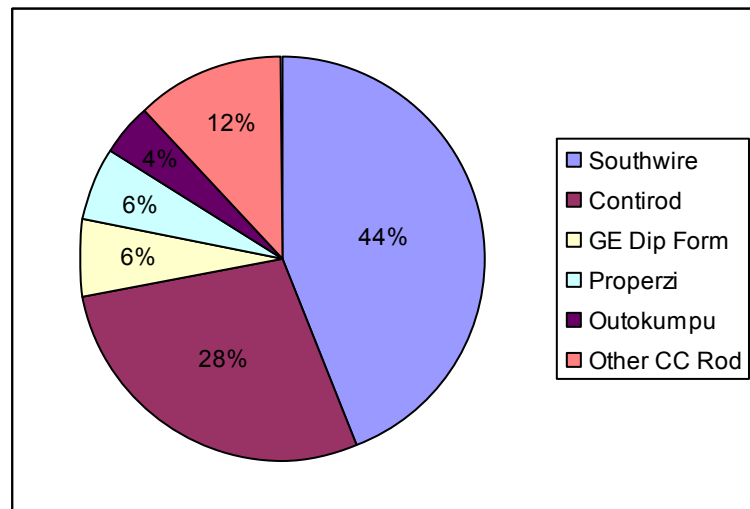


Figure 2.1 The capacity distribution of copper wire rod technologies. [9]

2.3.1 G.E. Dip-Form Process

The General Electric-USA dip-form process was introduced in 1964. This method produces 1.5-2 cm diameter rod directly from molten oxygen-free copper. The rod is generally used for production of fine and ultrafine wires. [1,3,5]

2.3.2 Hazelett Process (Contirod)

The process was originally developed in 1957 for zinc and was further refined in conjunction with Metallurgic Hoboken Overpelt (Belgium) to make it applicable to copper wire rod. The Contirod system based on the Asarco furnace, the Hazelett twin-band casting machine and continuous automatically controlled rod-rolling is also increasing in importance but not as much as the Southwire SCR system. [1,3,5,10,1,12]

2.3.3 Properzi System

The Properzi system is based on technology developed at La Farga La Cambre in Spain. The Properzi system is basically the same as the Southwire process except for slight differences in design of the casting wheel and configuration of the rod mill. [1,3,5,10,12]

2.3.4 Outokumpu Process(Upcast Method)

The Outokumpu process was originally invented and developed for Outokumpu's (Finland) own production to substitute for the manufacturing of high conductivity oxygen free wire bar in the late 60s(Conventional Method). During development three major goals have been kept in mind: [1,3,5,7]

- High quality
- Economy with moderate output
- Intermediate (cast) product as close to the final size as possible.

The process is based on the submerged die casting technique. The melt solidifies in a die, normally made of special graphite. The die is fixed at one end in a cooled copper jacket, through which the heat is transferred into the cooling media. [13]

The solidification front in the die is close to the lower end of the copper jacket. To avoid surface oxidation of the rod, there is an additional secondary cooling area so that the copper is cool enough when emerging into the atmosphere to stay bright, and it is ready for further processing without pickling or any other treatment. In Figure 2.2. the typical upcast line can be seen. [13]

The Upcast system produces around 30.000 tons/year or more of copper wire rod. The latest development is to cast 8 mm diameter copper wire rod directly. The system is also used for other applications, copper alloys, precious metals, zinc, cadmium and some special products. [13]

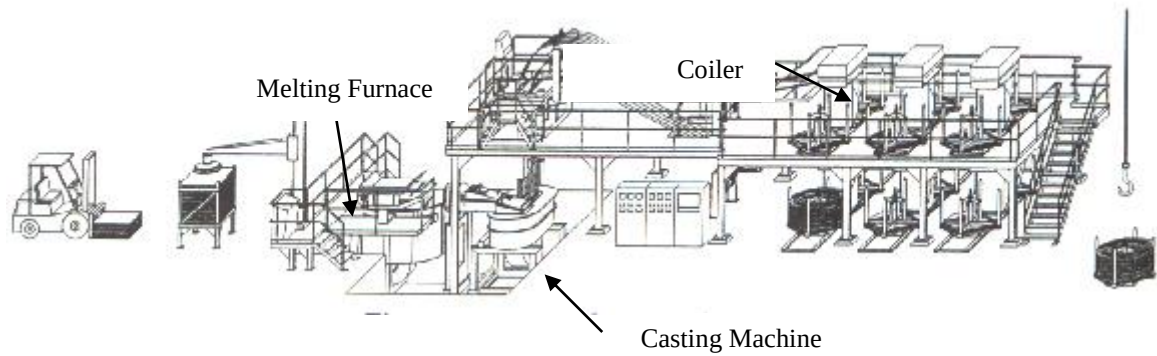


Figure 2.2 Typical 12-strand Outokumpu line. [13]

2.3.5 Southwire Continuous Rod Process

The Southwire Continuous Rod Process (SCR) has been successfully used over the years in several plants around the world for producing copper rod. The SCR has revolutionised the copper industry since its inception in 1964. There are at present over 50 SCR systems operating around the world producing approximately 50% of the world's copper rod. The systems operating around the world produce electrolytic tough pitch (ETP) copper rod in sizes from 8 to 22 mm in diameter at production rates of 6 to 50 tons/hour. (ETP rod is electrolytically-refined copper, which contains mostly oxygen as an impurity.) [3,14,15,16,17,18]

The SCR process is a combination of continuous melting, casting, rolling, pickling and coiling operations.

Copper cathode is melted in a vertical shaft furnace and transferred continuously to a cylindrical holding furnace which provides homogenisation of chemistry and uniformity of temperature. The molten copper is transferred continuously with the help of covered heated launders to a tundish, located directly above the casting machine. The tundish is equipped with an automatic flow control system to regulate the flow of metal on to the casting wheel and maintain a constant metal level. [1,3,6,16,17,18]

The casting machine consists of a copper alloy wheel having at its periphery a groove closed by means of an endless steel belt to form a continuous wheel mould. The casting wheel mould is cooled on all sides to solidify molten copper in less than 30 seconds. On exit from the casting machine, the cast bar is guided through an in-line bar preparation unit which removes the two belt side sharp corners. High

pressure water sprays are also provided to remove any surface scale or oxide. [3,5,16,17,18,19]

The bar then enters a no-twist rolling mill where it is reduced to the final rod size, from 6.35 to 23 mm, by means of a series of vertical and horizontal two roll stands. Upon exiting the last roll stand, the rod goes through an in-line alcohol or acid-based pickling and cooling system. The resulting bright copper rod is coated with wax to retard surface oxidation and is coiled continuously into packages weighing from 1.5 to 10.0 tones. [3,16,17,18,20,21]

2.4 Cathode Quality and Recommended Specifications

A consistently high quality cathode supply is a primary requirement for any successful rod manufacturing operation. One of the most important factors affecting the quality of copper rod is the type and amount of impurities in the base metal. Impurities play an extremely important role in determining the electrical conductivity, hot shortness, annealability and physical properties of unalloyed commercially pure coppers, both oxygen-free(OF) and electrolytic tough pitch(ETP). [16,17,18,22,23]

Around the world national standards vary on the acceptable limit of impurities in copper cathode with some allowing up to several hundred PPM of impurities. The British Standard on which the LME(London Metal Exchange) registration is based allows as much as 300 PPM. However, in Europe and the USA virtually all copper producers are obtaining impurity levels of 50 PPM or less(excluding oxygen) with over 100% IACS electrical conductivity. [16,17,18]

The ASTM and BS specifications shown in Table 2.1. have significantly tighter limits which are designed to help identify the best copper cathodes for use in electrical applications. Rigid control is placed not only on total impurities, but also on individual elements, which are detrimental to both the electrical and annealability properties. The BS is more rigid than the ASTM specification putting a maximum limit of 65 to 90 PPM (excluding oxygen) on total impurities and also providing tighter limits on individual and groups of specific detrimental elements. [16,17,18]

ELEMENT	BSI		ASTM		SOUTHWIRE SCR Process Users PPM
	Elements PPM Max.	Group PPM Max	Elements PPM Max.	Group PPM Max	
Selenium	2.0		4.0		-
Tellurium	2.0	3.0	2.0	5.0	<0.80
Bismuth	2.0		2.0		<0.35
Chromium	-		-		-
Manganese	-		-		1.35
Antimony	4.0		5.0		-
Cadmium	-	15.0	-		-
Arsenic	5.0		5.0		<1.0
Phosphorous					
Tin	-		10.0		0.8
Nickel	-		10.0		<3.0
Iron	10.0		15.0		3-11
Silicon	-	20.0	-	20.0	-
Zinc	-		-		-
Cobalt	-		-		<1.0
Lead	5.0	5.0	8.0		1.7-3.0
Sulphur	15.0	15.0	25.0	25.0	5-10
Silver	25.0	25.0	25.0	25.0	10-16
Oxygen	-	-	200.0	200.0	
Total Maximum		65.0		90.0	30

Table 2.1 BSI and ASTM Specifications for copper cathodes together with the chemical analysis of SCR process cathodes. [18]

The average chemical analysis of cathode produced by the companies(On Table 2.1 it is mentioned as Southwire) that use the SCR Process is also shown in Table 2.1. for comparison. It is clear from the table that the cathode meets both the individual and total impurity requirements of both specifications. [16,17,18]

2.4.1 Effect of the Impurity Elements

The effects of the impurity elements will be discussed under three main headings. The first is elements required within certain limits-eg. oxygen, the second is elements that are never desired-eg. hydrogen and the third is other impurities which have detrimental effects on copper quality.

2.4.1.1 Elements Required Within Certain Limits eg. Oxygen

Oxygen plays a very beneficial role in the continuous casting of copper by oxidising many of the impurities, which are present in copper, and precipitating them out of the solid solution. Therefore the detrimental effects of the impurities on resistivity are eliminated. This advantage is lost, however, in oxygen free copper where the impurities remain unoxidized and stay in solution causing a significant increase in the resistivity of the rod. The effect of oxygen on the conductivity of copper can be seen in Figure 2.3. [3,24,25]

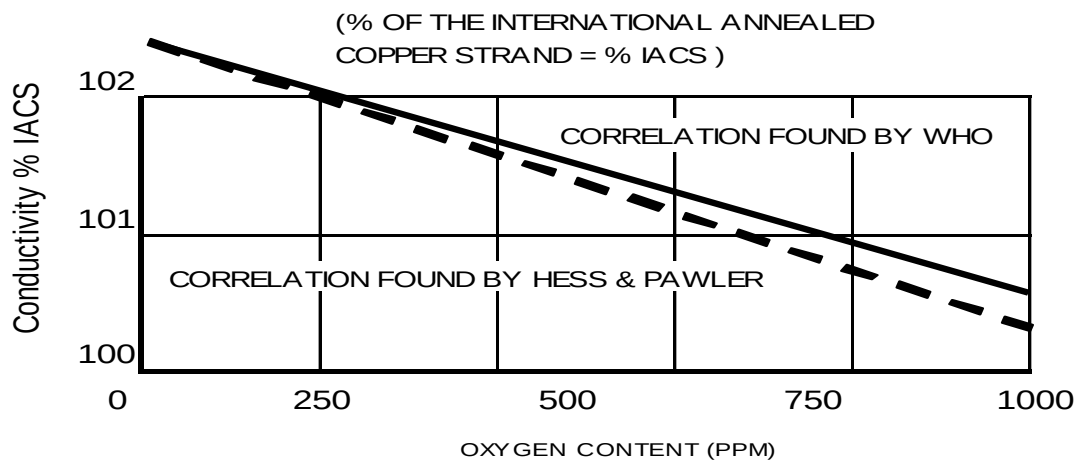


Figure 2.3 Effect of oxygen on the conductivity of high-purity copper(IACS). [26]

A 200 PPM minimum oxygen level is usually sufficient for impurity and hydrogen control. However levels as high as 450 PPM are occasionally used by some rod manufacturers. The excess oxygen precipitates as eutectic Cu_2O along the dendritic grain boundaries.(See Figure 2.4, Cu-O Phase Diagram) Upper limit controls are usually applied since too much Cu_2O in the microstructure can lead to central burst type failures during wire drawing. [1,16,17,18]

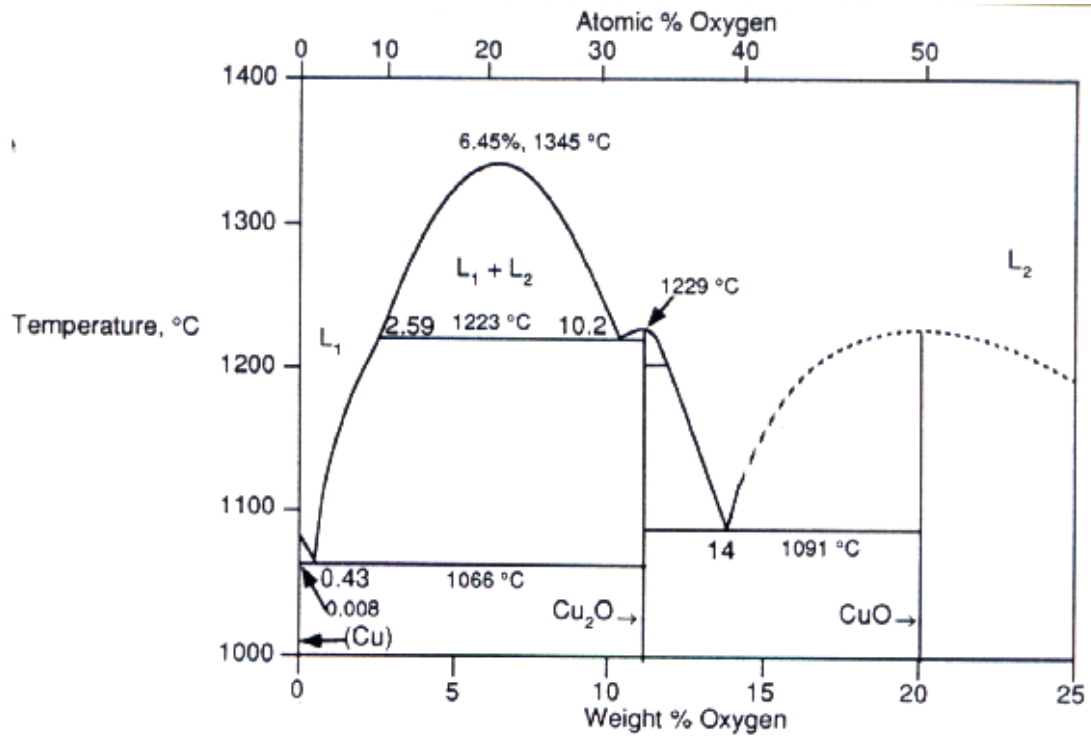


Figure 2.4 Cu-O phase diagram. [36]

The structure of the OF copper remains unchanged under the conditions of brazing or welding in a reducing atmosphere or vacuum. But the copper-oxide phase in tough-pitch copper decomposes leaving voids and causing embrittlement of the metal. When the material is subjected to cold-working, the copper oxide particles in ETP-copper act as centres of stress concentration. ETP-copper work hardens faster and fails at a lower strain than oxygen-free copper. So OF-copper can withstand considerably more deformation than ETP-copper before breakage occurs. [8,26]

2.4.1.2 Effect of Undesirable Elements eg. Hydrogen

Hydrogen is the most detrimental of all gases and excessive amounts of hydrogen (>2 PPM) in the molten copper cause hydrogen embrittlement leading to cracks along the grain boundaries and high porosity. Hydrogen dissolves readily in molten copper and its solubility increases with increasing temperature. It is believed that the source of hydrogen is the thermal decomposition of any organic material trapped in the cathode. [16,27,28,29]

High hydrogen together with deleterious impurities such as lead, bismuth, tellurium, sulphur, selenium, antimony and arsenic result in a synergistic effect making the

cast bar grain boundaries very susceptible to thermally and mechanically induced stresses which results in cracks during casting. [16,27,28,29]

2.4.1.3 Effect of the Other Impurity Elements

Bismuth: Bismuth is particularly insoluble in solid copper. At 800°C the solubility is 0.01% (wt%), at 600°C it is 0.001%, and at 300°C less than 0.0001%. Bi crystallises along the grain boundaries and has a very high diffusion rate. The main effect of Bi in copper is the high degree of embrittlement produced at the grain boundary network. Bismuth occurs in the form of films at the grain boundaries. Its embrittling effects are probably closely related to the development of these films, which depend on other factors such as grain size and thermal history as well as Bi content. [23,30,31]

Selenium: Selenium forms a compound, Cu_2Se , which is brittle and forms on the grain boundaries. This compound begins to melt at 1063°C. The solubility of Se in copper is 0.015% at 800°C, decreasing to 0.0001% at 600°C. The effect of Se is decreased by the presence of oxygen through the formation of Se_2O which, even if formed at the grain boundaries, will not cause embrittlement. [23,30,31]

Tellurium: Tellurium causes an effect similar to Se since it also forms a compound Cu_2Te that melts at 1051°C. [23,30,31]

Lead: Lead has a very limited solubility. At 800°C the solubility is 0.04% and at 500°C less than 0.001%. Lead crystallises along the grain boundaries since it is insoluble in solid solution. Serious difficulties are experienced in hot-working of copper unless it contains considerably less than these solubility limits. [23,30,31]

The relationship between lead content and electrical conductivity of copper indicates that in the range 0-25 PPM lead, every 5 PPM of lead reduces the conductivity of copper by about 0.12% and 0.10% IACS, respectively, for oxygen levels of 0.035 and 0.045%. (Oxygen can reduce the detrimental effects of lead) The lower rate of conductivity reduction by lead at higher oxygen levels may suggest that at higher oxygen concentrations there is a greater tendency for lead or other impurities to be converted to oxides which have a lower solubility in copper. [24]

Antimony: Antimony combines with Pb to produce low melting compound Cu_xSb_x formed at different temperatures. The most probable compound formed is Cu_3Sb which melts at 645°C . The large amount of Sb will also have a significant effect on the electrical conductivity and will also significantly raise the recrystallisation temperature of copper. [23,30,31]

The relationship between antimony content and the electrical conductivity indicates that at the level of 0.035-0.04% oxygen and for an antimony content range of 0-25 PPM, the conductivity is lowered by approximately 0.15% IACS for every increment of 5 PPM antimony content. [24]

Sulphur: Sulphur causes an effect similar to Se and Te.

2.5 Rod Classification Tests

All the rod producers in the world have classified their products according to different tests. All the rod impurity levels have to be appropriate for ASTM and BS standards. Generally, the rod producers use the letters of the alphabet or numbers to indicate the quality grades.

e.g. SA - Super A Grade Quality
 A - A Grade Quality
 B - B Grade Quality
 C - C Grade Quality
 H – Scrap

Or; 1 - First Quality
 2 - Second Quality
 3 - Third Quality
 4 - Fourth Quality
 5 – Scrap

The rod manufacturers generally use different methods for the determination of the product quality. These methods are as follows;

Oxygen Determination:

Historically, oxygen was first added to ETP copper wirebars in the range 200 to 500PPM to decrease the harmful effects of impurities by converting them to oxides. This traditional oxygen range is still used today for most continuously cast copper plants. For the determination of oxygen, the atomic absorption method is used. [26,32,33]

10x10 Twist Test:

This type of twist test has been used by manufacturers of copper rod to pinpoint surface imperfections that form during hot-rolling, for example, overfills, slivers, seams, laps, etc. This type of test is often used not only to assess overall surface quality levels of the incoming product but to predict subsequent drawability into wire. The 10x10 twist test consists of twisting one end of a 25 cm gauge length of rod 10 turns in one direction then reversing it to the original position, at a uniform speed, usually 60 RPM. After the test no small cracks or defects should be seen on the surface of the rod for the best qualities. For the other qualities some imperfections upto a limit can be acceptable. [34,35,36,37]

25/B Twist Test:

The 25/B twist test consists of twisting one end of a 25 cm gauge length of rod 25 turns in one direction then reversing it until it is broken. The sample has to withstand at least 20 turns for the better qualities. This method is also called the twist to destruction test which essentially measures the ductility of the copper and may be significant where a wide range of cathode qualities are used in manufacturing. [34,35,37]

Copper Oxide Surface Thickness:

For the best qualities, the copper oxide thickness on the copper rod has to be less than 400 Å. A simplified version of the electrolytic reduction test method is used for the determination of copper oxide thickness. [33]

Eddy Current - Ferrous Detector:

A combined eddy current and ferrous detector is used to detect defects such as minor cracks or seams or iron inclusions present in the surface and subsurface of the rod. The capabilities of the detectors have been enhanced to detect iron inclusions as small as 0.015 cm in diameter. The magnetic iron inclusion count is

used as a quality control tool for SCR process, to determine worn rolls in the mill. [16,38,39,40]

Dusting Test:

Dusting on copper rod is a serious problem specially for wire drawing operations due to die clogging and wire breaks. It is caused by the presence of rolled in oxides, flakes and loose copper particles on the surface of copper rod. The most popular method to determine the amount of dusting on the surface is the "Scotch Tape Method". This method involves twisting the rod and tightly wrapping a known length and weight of scotch tape around the rod sample. The tape picks up loose particles of copper and copper oxides from the surface of the rod. The tape is carefully removed and is weighed again. The difference in the weights of the tape gives the amount of dusting which is reported as "mg" of dust per 100 mm of tape or rod. [16,41,42]

2.6. Wire Drawing Process

The drawing of rod and wire is a technology of ancient origin, with Egyptian practices dating to 3000 BC. The relatively modern structural and electrical applications were developed in the late nineteenth century. The first continuous drawing machines were developed in Germany and England in the early 1870s. [43,44,45,46]

Drawing operations involve pulling material through a die by means of a tensile force applied on the exit side of the die. Most of the plastic flow is caused by compression forces, which arise from the reaction of the die on the metal. The process is usually performed at room temperature. The metal used for producing wire is usually in rod form, having been hot rolled or hot extruded. This rod is pointed at one end and drawn through the first die on to a capstan, which is driven round to provide the motive force. The wire is passed round this capstan, generally with a sufficient number of turns to provide the necessary frictional grip, and it is then passed through a second die and onto a second capstan. This arrangement is repeated through successive dies until the required diameter is attained, this final diameter often being as small as 0.04 mm. Reductions in cross sectional area per pass range from zero to about 45 percent. Usually, the smaller the cross-section is initially, the smaller will be the reduction per pass. Fine wires are usually drawn at 15 to 25 percent reduction per pass, and larger sizes at 20 to 45 percent. Reductions of more than 45 percent may result in lubrication breakdown. [43,44,46,47,48,49,50]

Successful drawing operations require careful selection of process parameters and consideration of many factors. Drawing speeds depend on the material and cross sectional area. They may range from 1 m/s to 2.5 m/s for heavy sections to as much as 50 m/s for very fine wire, such as that used for electromagnets. [45,46,48,49,51]

The major variables in drawing are reduction in cross-sectional area, die angle, friction along the die-working piece interfaces and speed. The cross section through a conical drawing die is shown in Figure 2.5. The entrance of the die (the bell) is shaped so that the wire entering the die will draw lubricant with it. The shape of the bell causes the hydrostatic pressure to increase and promotes the flow of lubricant into the die. The approach angle is the section of the die where the actual reduction

in diameter occurs. The approach angle, α , is an important process parameter. The bearing region does not cause reduction but it does produce a frictional drag on the wire. The chief function of the bearing region is to permit the conical approach surface to be refinished (to remove surface damage due to die wear) without changing the dimensions of the die exit. The back relief region allows the metal to expand slightly as the wire leaves the die. It also minimises the possibility of abrasion taking place if the drawing stops or the die is out of alignment. [46,48,49,5]

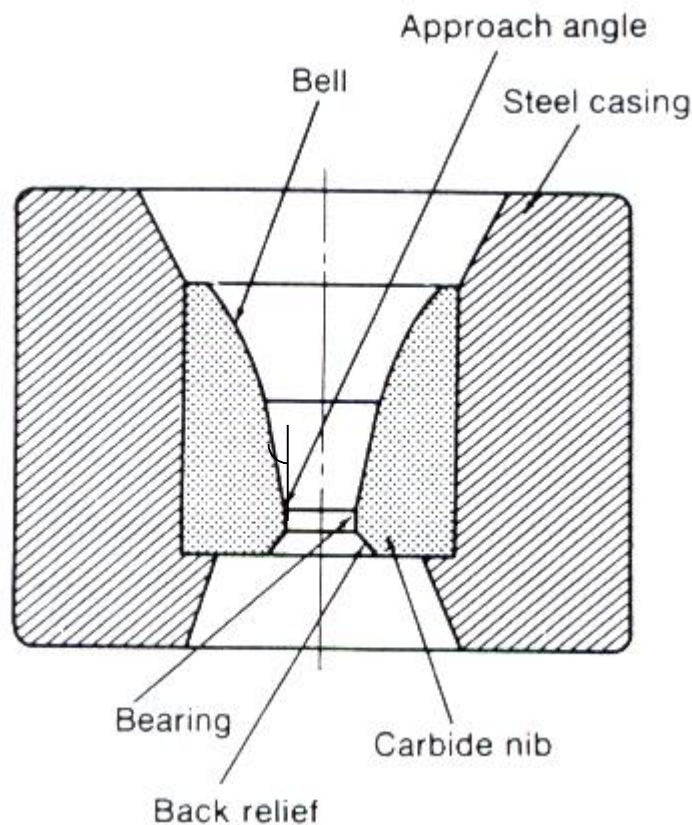


Figure 2.5 Cross section of a drawing die. [46]

Heat generation is a major concern in drawing operations. Although most rod and wire drawing is done cold, plastic deformation and friction can generate wire temperatures of several hundred degrees Celsius. This heat is only partially removed by interpass cooling, and since the dies conduct little heat, they get quite hot. [46,48,49]

2.6.1 Copper Wire Drawing Dies

The heart of the wire drawing operation is the material deformation that takes place inside the drawing die as the metal is drawn through it. A die has two purposes; the first one is to help provide suitable lubricating conditions and the second one is to produce the most appropriate deformation pattern and conditions in the metal being drawn. To obtain good deformation in a controlled manner, the drawing tool or drawing die, must have an appropriate special profile, which consists of four different and important parts- entrance, approach, cylindrical bearing and exit relief. (See Figure 2.5) The proportions of these four different regions in a die profile depend considerably on the wire material to be drawn. As a general rule, the harder wire materials demand a profile with smaller reduction angles and longer bearing surfaces. [3,52,53,54,55,56]

Until the mid-eighties the choice of material used in wire drawing dies was either tungsten carbide or natural diamond. The deciding factors are the material being drawn, the size of finished wire, the quality of surface finish required and perhaps most importantly, the cost-effectiveness of the complete set. [53]

Nowadays, in the non-ferrous industry, a third basic material is also used to manufacture successful wire drawing dies: synthetic diamond. [3,52]

2.6.1.1 Natural Diamond Dies

Since the second part of the 19th century, the wire industry has used natural diamond as a raw material to produce wire. Natural diamond is the ideal die material in terms of performance. Its hardness, wear resistance and fine microstructure guarantee a longer die life, greater accuracy and a superior finish than that achieved using tungsten carbide. The main drawback is its cost, since only high quality stones can be used. Therefore the use of natural diamond is restricted to situations where small diameters and highly polished surface finishes are required. The wire diameters most commonly drawn with diamond dies are those applicable in size for paper clips down to the ultra-fine wire for the electronics industry. Diameters of 4.00 to 0.010 mm are quite common. [3,52,55,56]

A diamond wire die consists of a corrosion-resistant metal case into which is centred a carefully selected and precisely oriented, high quality industrial diamond, mounted in a thermally set metal core under controlled stress. [3,52]

2.6.1.2 Carbide Dies

During World War 1, Germany was short of natural diamonds for wire drawing dies and many attempts were made to discover a substitute. The end result was the development of a carbide die that was made possible by the addition of an auxiliary metal (cobalt) to tungsten carbide. The firm of Friedrich Krupp developed this commercially and today the straight grades of carbide are still basically the same. [52]

The general application of tungsten carbide dies started in the late 1940s, when traditionally used softer die materials could no longer match the improved modern drawing equipment and procedures. Carbide dies came into use for non-ferrous wire drawing because of their excellent wear characteristics. Certain special non-ferrous applications may be exceptions to this rule but most drawing of copper and aluminium wire is done with natural or polycrystalline diamond dies for the finer sizes and carbide dies for 1.63 mm and above. The tungsten carbide die is the cheapest die form to produce, but has a lower life expectancy than either natural or synthetic diamond. It is used for copper wire production in the larger rod breakdown sizes. [52,55]

2.6.1.3 Synthetic Diamond Dies

In the mid-eighties, a third material became available, bridging the gap between tungsten carbide and natural diamond. This material is known as polycrystalline diamond. Diamond is one form of pure carbon. Since the dawn of time, man has tried to make diamonds but was not successful using a repeatable process until 1954. Then a team of scientists at General Electric Co. was able to convert one form of carbon, graphite, into another form of carbon, diamond. Thus was born synthetic diamond powder, a product now manufactured by many companies in many countries. The transformation of this synthetic diamond powder into the hard, solid core of a wire drawing die required twenty more years of research and development which still continues today. [52,55]

The first marketable synthetic diamond die blanks were introduced by General Electric Co. in 1974 under the name Compax. Compax diamond die blanks are a combination of synthetic polycrystalline diamond and cemented tungsten carbide. The two materials are produced as an integrated unit by means of a patented high temperature-high pressure process closely approximating the conditions which cause natural diamonds to form. [52]

Compacted polycrystalline diamonds are not quite as hard as natural diamonds. Because there are various possible hardnesses for such compacts depending on the temperature gradients used in the manufacture, the grain size of the graphite, the nature of the catalyst used and other variables, an exact numerical value for the difference in hardness cannot be stated.

2.6.2 Lubrication in Copper Wire Drawing

Copper wire is drawn in a wet operation. From 8 mm wire rod to 4 micron super fine wire, the wire runs through approximately 100 drawing dies which must be lubricated. Drawing speeds of up to 90 m/s are reached. The raw material and its method of preparation have considerable effects on friction, wear and lubrication. As a function of the wire diameter, the requirements of the lubricant vary. In rod breakdown the lubricating properties of the lubricant are nearly always the most important. In the case of fine wires, however, the cleaning effect for trouble-free running is likely to have increased importance. [57,58,59]

In copper wire drawing, lubricants are produced under two main categories: liquid and paste. The newer synthetic liquid products are easier to control and run cleaner. (Clean means the development of bacteria, etc, is less in the emulsion) The paste products are lower in price but run dirtier and require more maintenance. The lubricants are mixed with water in a reservoir and circulated to the die continuously. Compounds vary in the type and amount of lubricant they contain to suit the initial size of wire and number of draws. [3,52]

2.7. Theory of Wire Drawing

Wire drawing appears to be one of the simplest of the working processes, but in some ways it is one of the more complicated. The initial equiaxed grains are elongated in the drawing direction and compressed in the transverse direction. A

grain at the surface will be elongated more than a similar grain at the core, due to the redundant shear which characterises the material flow in the drawing. Friction and redundant work are the two main parameters which have major effects on the power requirements for drawing. It is therefore important to minimise these to achieve the most economical drawing conditions. [60,61,62]

Figure 2.6. represents a billet and die. The billet is a material of assumed constant strength. In form, it is a cylindrical rod of radius R_o . The rod is reduced to radius R_f by forcing it to pass through the conical converging die. Reduction is measured from the cross-sectional area of the billet at the entrance to the die (A_o) to that at the exit (A_f). m is the friction factor between die and billet. [52]

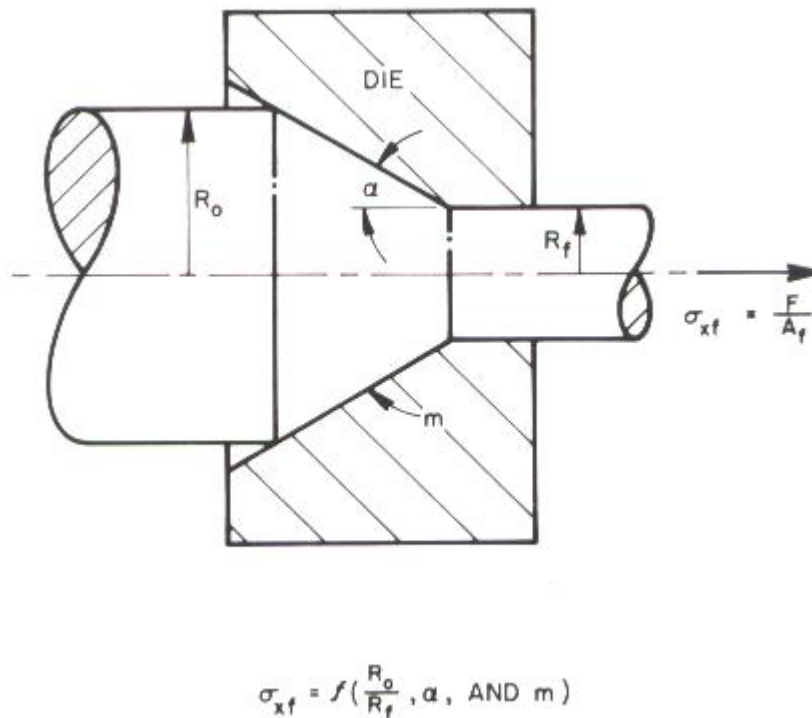


Figure 2.6 Drawing Force. [52]

Three variables involved in the reduction process are:

- 1) The radius ratio R_o/R_f or one of its related expressions, area ratio $(R_o/R_f)^2$ or relative reduction where R_o is inlet wire radius, R_f is reduced wire radius and A_o and A_f are cross sectional area of inlet wire and reduced wire.

$$(A_0 - A_f) / A_0 = 1 - A_f / A_0 = [1 - (R_f / R_0)^2]$$

2) The semicone angle of the die, α , i.e., the die half angle or approach angle.

3) Friction between the die and the rod.

At the entrance and exit of the die, the wire moves as a rigid body in the axial direction. If the wire enters the die at velocity v_0 and leaves it at velocity v_f , then, by volume constancy, the ratio of these velocities, for sound flow with no fracture, is $v_0 / v_f = (R_f / R_0)^2$. [52]

The plastic deformation occurs under the influence of the die. The wire bulges or converges before coming in contact with the die. The cross-section of the wire is reduced as the wire elongates while flowing through the die. [52,63,64]

2.7.1 Mechanics of Wire Drawing

During the wire drawing process there are three main contributions to the work done.

- Useful Work: Work that directly contributes to the required shape change.
- Work done against friction: Friction between the material and the die in the approach region.
- Redundant work: Work that is done deforming(shearing) the material, that does not contribute to the overall shape change.

2.7.1.1. Useful Work

The useful work is simply the work that is required to produce the shape change in the wire. The increment of work (∂W) done in increasing the length of a cylinder by a small amount ∂l is given by the following equation where σ_0 is drawing stress and A is the cross sectional area of wire: [46]

$$\partial W = (\sigma_0 \cdot A) \cdot \partial l$$

If the drawing force is F , the useful work done per unit volume(V) in drawing the rod from its starting position (adjacent to the die) to the full length l_1 , is given below where σ_D is the drawing stress of the wire: [46]

$$W/V = F \cdot l_1 / A_1 \cdot l_1 = F / A_1 = \sigma_D$$

2.7.1.2 Friction Work

Whenever there is a relative motion between two surfaces, there is resistance to this motion and this resistance is called friction. In wire drawing, friction increases the drawing force, because work has to be supplied to overcome that friction. [63,64]

The work done against friction will depend on the coefficient of friction between the material and the die. When the coefficient of friction (μ) increases then the drawing load will increase. If the approach angle (α) increases the contact area between the material will decrease, and hence the drawing load will decrease. (See Figure 2.7)

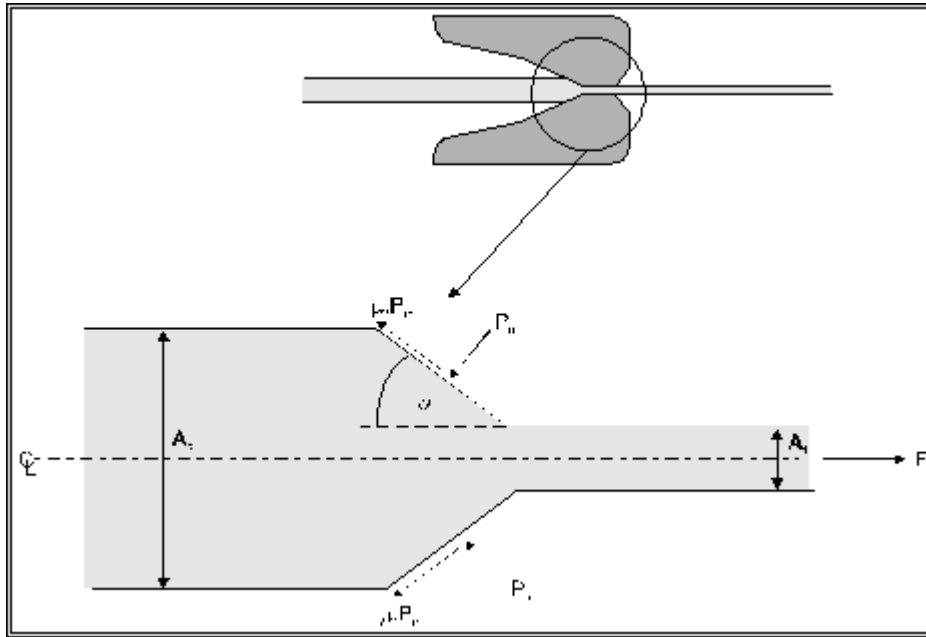


Figure 2.7 The effect of approach angle on friction. [63]

Consider pressure exerted by die:

P_m = Mean Pressure

F = Drawing Force

$(A_0 - A_1 / \sin \alpha)$ = Conical contact area

Consider equilibrium of forces in horizontal direction:

$$F = \mu P_m \cdot (A_0 - A_1 / \sin \alpha) \cos \alpha + P_m \cdot (A_0 - A_1 / \sin \alpha) \sin \alpha$$

For low coefficients of friction we can assume that:

$$P_m = F^* / A_0 - A_1$$

F^* = Drawing force when $\mu = 0$

$$F = \mu \cdot F^* / A_0 - A_1 \cdot (A_0 - A_1 / \sin \alpha) \cos \alpha + F^* / A_0 - A_1 \cdot (A_0 - A_1 / \sin \alpha) \sin \alpha$$

$$F = \mu \cdot F^* \cdot \cot \alpha + F^*$$

Dividing through by A_1 gives:

$$\sigma_D = \sigma_D^* (1 + \mu \cdot \cot \alpha)$$

$\sigma_D^* =$ Drawing stress when $\mu = 0$

$$\sigma_D^* = \sigma \cdot \ln (A_0 / A_1)$$

Therefore:

$$\sigma_D = \sigma \cdot \ln (A_0 / A_1) (1 + \mu \cdot \cot \alpha) \quad [46]$$

For consistency instead of $\mu = m / \sqrt{3}$ is used by Von Mises. ($\mu = m / \sqrt{3}$)

2.7.1.3 Redundant Work

During wire drawing when the wire enters the die the material is sheared in one direction and when it exits the deformation zone the wire is sheared again. This shearing requires work to be done that does not contribute to the overall shape change of the material. This type of work is called redundant work. [46,63]

In Figure 2.8 an element (δr) of length is entering the deformation zone at a radius r . As it enters the deformation zone L , it shears through an angle θ rads. If the shear flow stress is K , then the work done per unit volume in shearing the element through an angle θ is given by : [46]

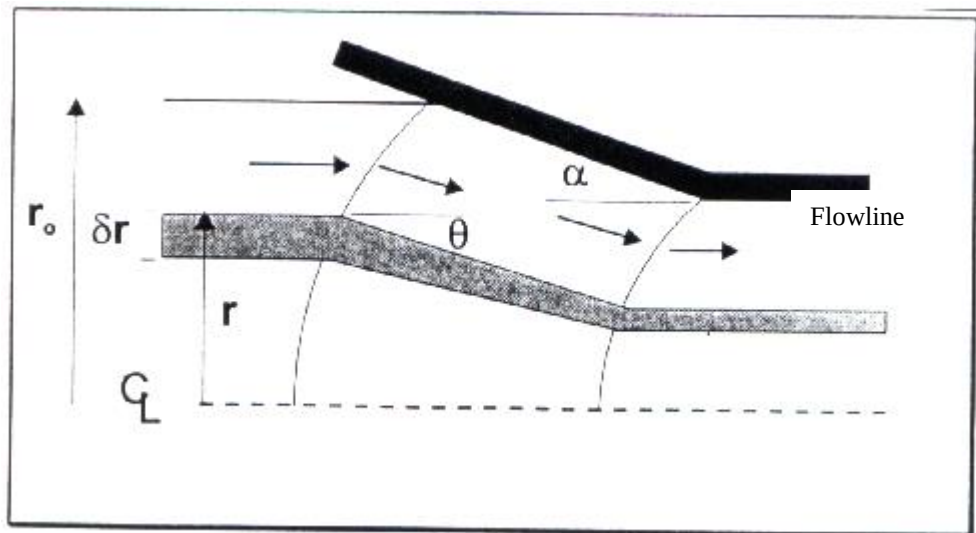


Figure 2.8 Flow line of material through a die. [63]

$$\partial W = V \cdot K \cdot \theta = 2 \cdot \pi \cdot r \cdot \partial r \cdot \partial x \cdot K \cdot \theta$$

θ (Radians) can be written as a function of r :

$$\theta = (r / r_0) \cdot \alpha$$

Total work done at entry can be calculated:

$$W = 2 \cdot \pi \cdot \partial x \cdot K \cdot \alpha / r_0 \int r^2 \cdot \partial r = 2/3 \cdot \pi \cdot K \cdot \alpha \cdot r_0^2 \cdot \partial x$$

Work done per unit volume is therefore:

$$W/V = 2/3 \cdot \pi \cdot K \cdot \alpha \cdot r_0^2 \cdot \partial x / V = 2/3 \cdot \pi \cdot K \cdot \alpha \cdot r_0^2 \cdot \partial x / \pi \cdot r_0^2 \cdot \partial x = 2/3 \cdot K \cdot \alpha$$

Total redundant work per unit volume σ_R (or the stress required to overcome redundant work, is given by: [46]

$$\sigma_R = 4/3 K \cdot \alpha$$

By Tresca the shear stress is half the normal stress. Therefore:

$$K = \sigma/2$$

Therefore

$$\sigma_R = 2/3 \cdot \sigma \cdot \alpha$$

The redundant strain is simply can be defined as $2/3 \cdot \sigma \cdot \alpha$

Therefore the drawing stress taking into account friction and redundant work is: [46]

$$\sigma_D = \sigma \cdot \ln (A_0/A_1)(1+\mu \cdot \cot \alpha) + 2/3 \sigma \cdot \alpha$$

or

$$\sigma_D = \sigma \cdot \ln A_0/A_1 + \mu / (\tan \alpha \cdot \sigma \cdot \ln A_0/A_1) + 2/3 \cdot \sigma \cdot \alpha$$

2.7.2. Sound Flow vs. Other Patterns

Sound flow occurs only within a limited domain among all possible combinations of die angle, reduction, and friction values. In Figure 2.9. the effect of tool angle on the mode of flow and on the drawing force can be seen. [52,63,64]

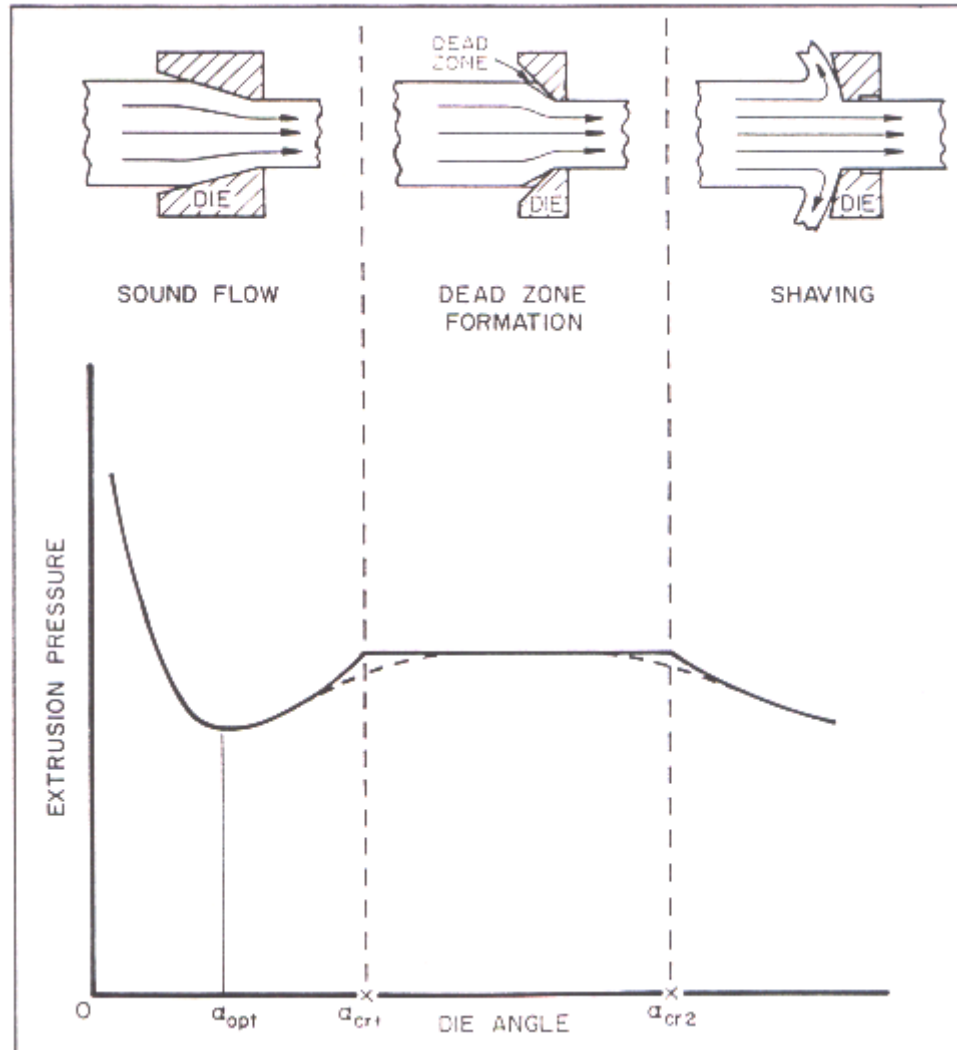


Figure 2.9 Effect of tool angle and mode of flow on drawing force. [46]

In the range of sound converging flow the drawing stress is high for very small cone angles because of high friction losses. With increasing cone angle, friction losses decrease and so does drawing stress until an optimum angle is reached. Beyond this, further increase in die angle causes increasing drawing stress because of increasing shear or redundant deformation due to excessive distortion. This gradual rise in drawing stress continues until a first critical angle is reached, at which point ordinary sound flow changes into flow with a dead zone formation. With the change

in flow pattern the slope of the characteristic curve describing the drawing stress undergoes a discontinuity; thereafter the drawing stress continues unchanged with increasing die angle up to a second critical angle at which pure shaving begins. [46,63,64]

If sound flow could be continued for cone angles larger than α_{cr1} , the consequent excessive distortion and redundant deformation would lead to excessive drawing force. The angle of the dead zone, however, is smaller than that of the die; thus, the material has found a way to eliminate excessive distortion and to minimise total process energy. For angles smaller than α_{cr1} sound flow with no dead zone requires lower drawing stress. [46,63,64]

2.8. Modelling of Wire Drawing

The reason for modelling any manufacturing process is to predict the microstructure, and properties of the material as it is processed and the deformation loads required.

Figure 2.10 shows some of the approximations that can be used to describe the behaviour of a material during a deformation process. The approximation used depends on the situation being modelled. The one that has been used most widely is shown in Figure 2.10(a), and is for a rigid-plastic material which exhibits no work hardening and shows ideal plastic behaviour. [65]

Figure 2.10.(b),(c) and (d) show progressive refinement of the model by introducing elasticity and work hardening. Figure 2.10.(e) shows a mathematical model which is useful for a ductile material with significant work hardening and is often used for ductile materials formed at relatively low temperatures. [65]

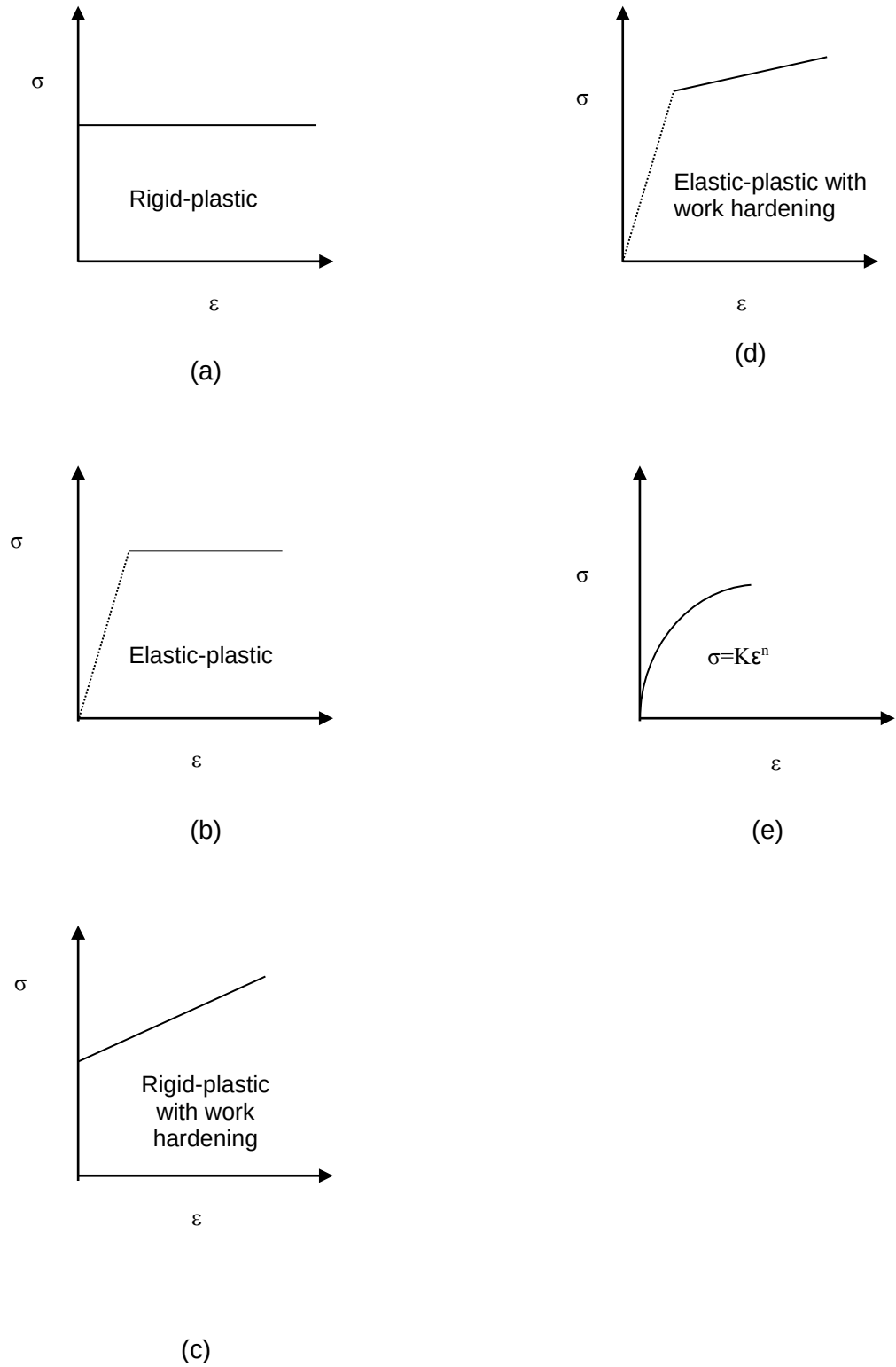


Figure 2.10 Some approximations to material stress-strain curves. [65]

2.8.1 Finite Element Method

Finite Element Analysis is a numerical modelling technique that requires a significant amount of computer power. The user does not have to solve all the mathematical equations, since this is done by computer. In metalworking plasticity considerations, the problems concerned with elastic and inelastic stress analysis can be solved by FEM. [46,65]

FEM splits the whole of a body which is going to be deformed, into a series of simple geometrical elements that are joined together at points (called nodes). The result of this operation is called a mesh. After the simulation with the help of the mesh structure, predictions of the mechanical properties can be made. The main use of FEM is to determine the distribution of stress and strain in plane stress, plane strain and axisymmetric conditions. The main disadvantage is that a large number of nodes are needed to model plastic flow together with a very large number of iterations needed for materials that work harden. This means that significant computing capacity is needed. This makes it very expensive. FEM techniques are becoming more popular as the price of computing power comes down. [46,65]

FEM can be a very effective tool for simulating deformation. The influence of die geometry, preform design, friction, material properties and defects can be investigated. Large deformations in metalworking generally cause the initial FEM mesh to distort excessively and so it becomes difficult to produce reliable information. When this happens it is necessary to remesh by generating a new mesh within the boundary of the deformed material. [46,65]

Kobayashi achieved a practical adaptation of the FEM for metalworking analysis with a technique called the matrix method. In this method, elastic strain was neglected, a reasonable simplification when considering the larger plastic strains. It assumed a rigid plastic behaviour and therefore large strain increments decreased the requirements of the computer. Kobayashi called this matrix method ALPID (Analysis of Large Plastic Incremental Deformation) and with the help of ALPID stress, strain, strain rate, particle and temperature distributions within a deforming material were investigated. [46,66]

.9 Classification of Wire Breaks and Drawability

In copper wire drawing, although there have been technological advances in parameters such as drawing speed, lubrication, die materials and die design, the basic process of wire drawing has not been changed. Wire breaks and their causes and prevention are of great importance. Determination of the cause and appropriate remedy for breaks are the two major steps in improving the process efficiency. [65]

Prior to the development of continuous production methods, drawing feed stock was produced via the batch rod rolling of copper ingots. During this process little effort was made to protect the rod surface from oxidation, and to maintain continuity during drawing the short rolled rod bars were welded together. As a result most wire breaks resulted from surface oxides, or welding defects. With the onset, in the 1960's, of continuous methods for the production of drawing feed stock, with increased oxidation protection, the severity of the wire break problem has been significantly reduced.[27,65]

Applications which require super fine(0.05-0.1 mm) and ultra fine(0.02-0.05 mm) copper wires have increased significantly recently. Breaks in ultra-fine wires have a great influence on the productivity of the drawing process. Sophisticated technological improvements have been developed in the continuous casting, rolling and pickling of copper rod which has permitted the production of copper rod of suitable quality for drawing to ultra fine wire sizes. [66,67,68]

Wire breaks may be divided into two broad categories: [69,79]

1. Breaks due to defects introduced in the bar casting and rod rolling processes; these are referred to as material defects.
2. Breaks caused by defects introduced in the wire drawing and subsidiary processing stages and generally termed wire drawing process defects.

In practice it is not always possible to distinguish between the two broad categories described above. Breaks may be due to a combination of factors.

2.9.1 Wire Breaks and Drawability

There is a very strong relationship between the terms “drawability” and “wire break”. Drawability is defined as the weight of of drawn wire per break at a given size:[6,71,72,73]

$$\text{Drawability} = \text{Mass of Wire Drawn} / \text{Number of Breaks}$$

This parameter is of great industrial importance as it is related to the downtime and the profit of producers.

Wire breaks occur when the drawing stress exceeds the strength of the wire. Wire breaks during production can be the result of either poor quality input material or drawing process faults. The cause of the break can normally be identified by the characteristics of the fracture surface. [71]

To improve the drawability of copper wire it is necessary to accurately identify the source of wire breaks. It is further necessary to relate both good and bad drawability to the copper casting and rolling conditions to identify and remedy areas which generate problems. A constant known as the drawability index has been developed to characterise the drawing behaviour of a particular source of copper. The drawability index is defined as follows:[72]

$$\text{Drawability Index} = \text{Drawability} / (\text{Final Wire Diameter})^2$$

The drawability index is a constant for a particular source of copper irrespective of the final size drawn. It will increase if the drawability of the copper source improves. Using this relationship it is possible to predict the performance of a source of copper in terms of kg/rod source break for any size of wire not previously drawn. [72]

For instance, for wire bar copper produced in the 1970s, values of 100 kg/rod source break achieved at 0.2 mm diameter were considered satisfactory. With the introduction of continuously cast copper 10-15 years ago the performance of wire drawn to 0.2 mm diameter improved from 600 to 1000 kg/rod source in the early 1980s. [72]

2.9.2 Inclusion Breaks

An inclusion is a foreign particle which gets embedded during casting, rolling or drawing. In other words, it is an internal or surface defect consisting of a foreign body located within the copper rod or wire matrix. An inclusion break will occur when the wire has been drawn to a size approximately twice the diameter of the inclusion. (A general rule of thumb) Depending on the diameter and location of the inclusion, the wire could exhibit a reduction in cross-sectional area or neckdown. (See Figure 2.11.)[65,74,75]

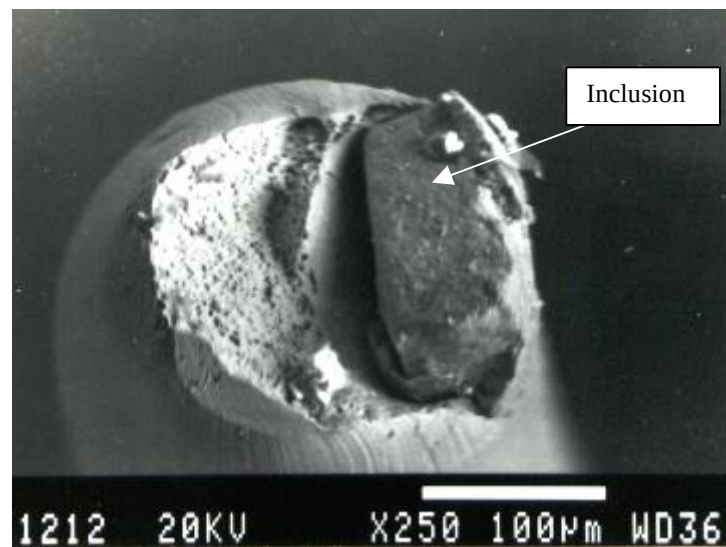


Figure 2.11 Scanning electron micrograph of an inclusion break.

Inclusion breaks can be divided into two main categories, those inclusions that derive from the original casting process (inclusion breaks), and those that are incorporated into the rod during the drawing process (drawn in inclusion). In both cases the inclusion may still be present in the wire after the break. Here it is possible to ascertain the nature of the inclusion and from this the origin can be determined. However in certain cases the inclusion can fall out prior to examination. Obviously in this situation the only way in which the origin of the inclusion can be determined is from the wire break geometry. We therefore have four sub categories of inclusion break: [76,77]

1. Cast Inclusion Present Break
2. Cast Inclusion Absent Break
3. Drawn-in Inclusion Present Break
4. Drawn-in Inclusion Absent Break

1. Cast Inclusion Present Break:

Wire failure characterised by the presence of inclusions (magnetic, non-magnetic or combination of both) at the fracture surface. Wire breaks can exhibit different fracture appearances, depending on the mode of failure and inclusion size.

2. Cast Inclusion Absent Break:

Wire failure characterised by a shear fracture having a cavity on one side. The cavity is created by an inclusion, which has fallen out during or after fracturing. Inclusions (magnetic or non-magnetic) which are present in the matrix of the wire initiate the cracking process. As the drawing continues, the inclusion breaks away from the wire matrix and falls out during final rupturing resulting in a shallow cavity. The inclusion absent break has a smooth inner surface, where the inclusion was in contact with the copper, and an irregular outer rim where the wire failed in tension.

3. Drawn-in Inclusion Present Break:

Wire failure characterised by the presence of inclusions on the surface or subsurface of the wire. Foreign particles can be easily introduced below the surface of the wire during drawing. Hard foreign particles (magnetic or non-magnetic) which are present in the die or lubricating solution can be drawn into the surface of the wire which will eventually result in a wire break. It is not so easy to distinguish between the inclusion present break and drawn-in inclusion break by looking at the breakage surface. A chemical analysis (EDS) is necessary to determine the source of the break.

4. Drawn-in Inclusion Absent Break:

Wire break characterised by the presence of a depression, which was caused by an inclusion. The inclusion was introduced into the wire surface during the drawing operation. A foreign object (ferrous or non-ferrous) introduced into the rod or in the lubricating solution and drawn into the wire is responsible for producing a major surface defect. The defect will produce concentration of stresses during further drawing that results in a wire break. A characteristic crater-like void is present in the wire showing traces of the missing embedded foreign particle.

2.9.2.1 Fracture Mechanism

The mechanism of fracture for macro-inclusions (≥ 50 microns in diameter) can be visualised with the aid of Figure 2.12. Here d represents the diameter of the inclusion, D represents the wire diameter at the exit of the die, and T represents the tension in the wire. [65]

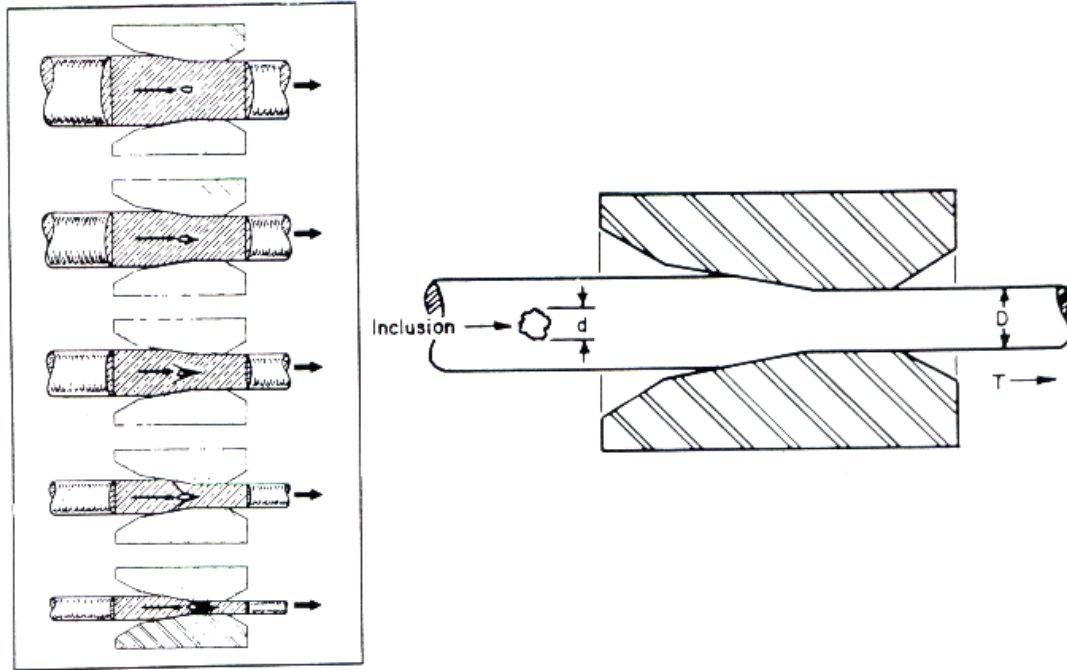


Figure 2.12 Schematic diagram of a copper wire, during drawing, containing an inclusion. [65]

When a wire containing an inclusion is drawn to the point where the inclusion diameter is critical (d becomes significant with respect to the diameter of the wire D), a reduction in cross-sectional area is produced. It is assumed that there exists a critical inclusion size, d_c , for a given “down stream” diameter D and that the condition for a break is: [66]

$$d \geq d_c$$

Now the critical inclusion size d_c depends upon D as well as the tension, T :

$$d_c = D f(T)$$

Where $f(T)$ contains a functional dependence of d_c upon the tension, T . For simplicity, assume that

$$f(T) = K / T^n$$

Where K is a constant of proportionality which may, itself, be a function of other parameters such as the drawing speed, temperature, or the amount of “flexing” between capstan and die, and n is an empirically determined number.

Then

$$d_c = D K / T^n$$

and the condition for a break is now:

$$d \geq D K / T^n$$

2.9.3 Central Burst (Cuppy Break, Cup and Cone Break)

The characteristics of cuppy wire breaks are a deep cup and a typical cone as shown in Figure 2.13. The presence of defects at the centre of a wire can contribute to the problem of cuppy breaks. The causes of this type of wire break are one or all of the following: [77]

1. High concentration of copper oxide particles or stringers in the central portion of the wire.
2. Presence of a micro particle of inclusion (magnetic or non-magnetic).
3. Improper die geometry, worn capstans, uneven entrance into a die, insufficient die lubrication or incorrect die reduction or entrance angle, excessively long land or bearing surface in the die.

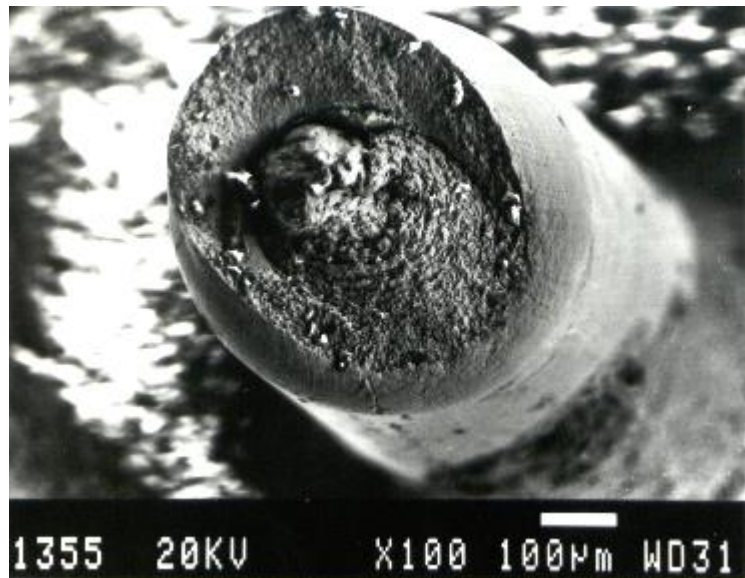


Figure 2.13 Cone part of a central burst type of wire break due to high oxygen content of about 700 ppm.(From current work)

Published work has shown that the presence of second phase particles reduces the ductility of copper and wire drawing experience has confirmed that with increasing oxygen content, cup and cone breaks become more likely. A high incidence of cup and cone breaks, particularly in the second stage (Wire drawing operation in another machine for reducing the diameter of the wire to finer sizes) of wire drawing is probable with oxygen contents in excess of 1000 PPM. Below 400-PPM oxygen, it has not proved possible to generate this type of defect under laboratory conditions. [82]

2.9.4 Checked Wire (Chevrons, Crows Feet or “V” Shape Defects)

Checked Wire are cracks on the wire surface in the form of an arrow tip. These faults are in a line with the tips pointing in the drawing direction and can cover a length of up to 1 m. A wire with this type of damage is extremely brittle and may tear in the course of further deformation. A checked wire break usually occurs at an angle of 45° to the wire axis without any necking as can be seen in Figure 2.14. This is characteristic of a brittle fracture. The checks could originate by physical abuse, poor die geometry, die misalignment a localised high oxygen concentration in the surface due to high oxidation on the wire surface. [70,77]

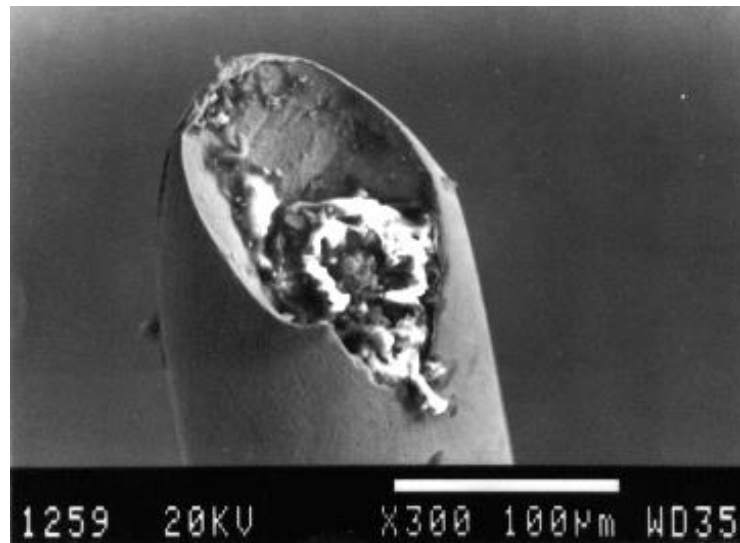


Figure 2.14 Checked wire defect.

Micro cracks start to develop on the wire surface when excessive compression becomes effective on one side of the wire. These excessive stresses can cause very high work hardening rates and differential metal movement from the surface to the inside. A common cause of this defect is the incorrect entrance of the wire into the die during drawing. [27,65]

2.9.5 Macroporosity (Hollow End, Pressed Hollow)

A break caused by macroporosity displays a funnel-shaped depression, as shown in Figure 2.15. The internal walls of the cavity are smooth and free of impurities and this zone has suffered no tensile stress during the drawing process. The male portion of the core does not extend to the end of the female portion. These faults can be formed during casting, either by excessive gas in the molten metal or by solidification shrinkage in the centre of the casting. During hot rolling, the pores may be closed depending on how big they are. The increased oxide content can lead to breaks similar to cuppy fractures. [65,70]

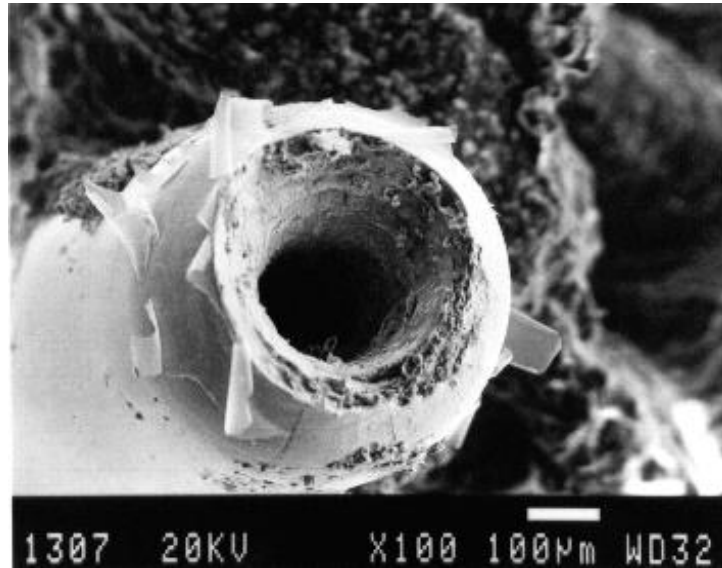


Figure 2.15 Scanning electron micrograph of a macroporosity type break exhibiting a characteristic “funnel-shaped” depression.

With good drawing practice, small central casting inhomogeneties would probably give no problems. However, if drawing practice is unsatisfactory, these small central defects may initiate cuppy fractures.

Macroporosity can be prevented by several methods which include casting copper without excessive gas content and providing sufficient cooling at the early stages of solidification to avoid a molten centre when the casting departs the wheel.

2.9.6 Tension Break

Wire failure characterised by a significant reduction in area(neck-down) and a small crater at the break point, as shown in Figure 2.16. A tensile fracture occurs when the drawing stresses exceed the ultimate tensile strength of the wire. The excessive tensile stress, results ultimately in a reduction of the wire cross section and its breakage. There are various causes for the tension type fracture. These include: improper or inadequate lubrication, improper die geometry, the accumulation of metal fines in the die entrance, mechanical abrasion, and extensive tensile stress or jerks from the drawing machine. [70,77]

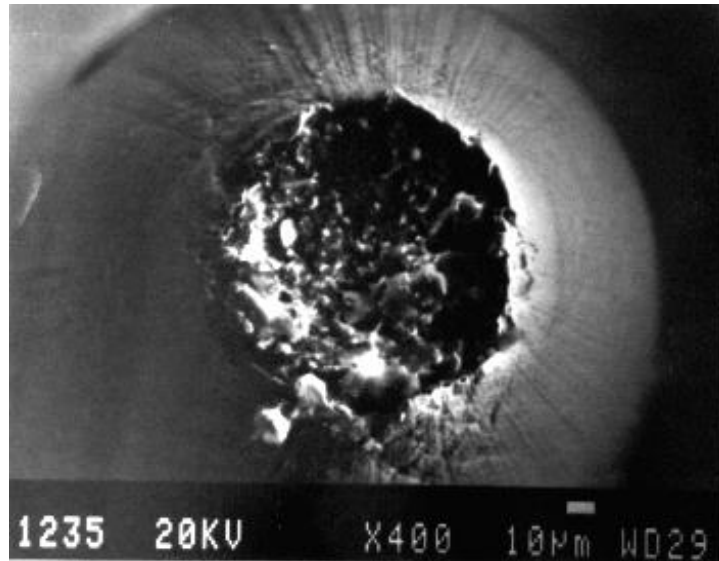


Figure 2.16 Scanning electron micrograph of tensile-type fracture showing crater-like fracture formation.

Tensile failures in copper wire are easy to identify. The ductility of copper results in the formation of almost identical cups in each half of the fracture. These breaks are well defined because the wire is necked down, and a small cup-cone at the break is a visible characteristic. With continuous cast rod, however, the neck-downs still occur, but the small cup may be missing due to impurities at the centre of the rod. [52]

2.9.7 Split End

Wire fracture characterised by a large crack resulting in a split in the middle of the wire, as shown in Figure 2.17.

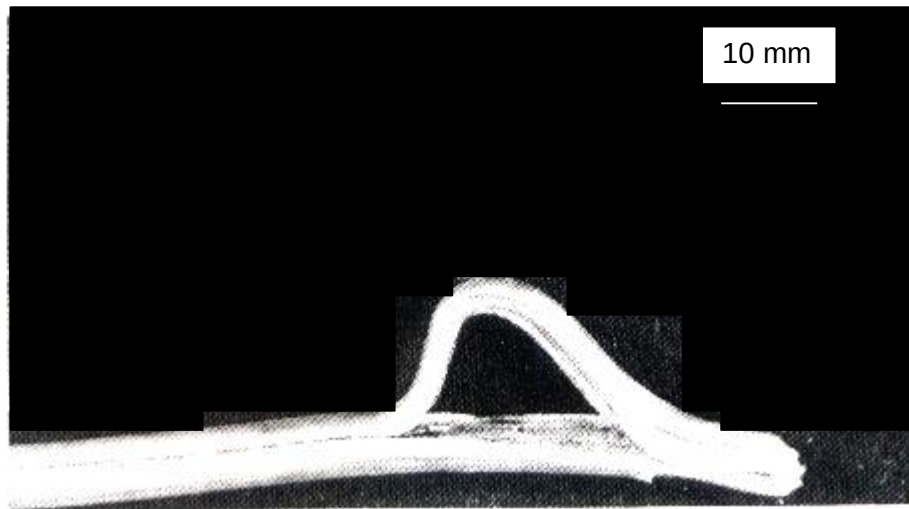


Figure 2.17 Presence of a heavy copper oxide slag in the fracture surface. [77]

This type of wire break is found less often in the fine wire range. The possible causes of a split end failure are : [77,78]

- Presence of a heavy copper oxide slag in the cast bar which is rolled into the rod.
- High concentration of copper oxide particles in the cast bar which remained undistributed resulting in a rod with a brittle centre and oxide stringers.
- Introduction of a foreign substance during casting operation or prior to rolling operation.
- Introduction of rolled-in copper fines prior to rolling operation.

2.9.8 Slivers

The sliver fracture is recognisable by a lap or folded piece of metal adjacent to the fracture area, as shown in Figure 2.18. In a majority of cases, the sliver is separated from the main body by a layer of unreduced cuprous oxide (Cu_2O) formed during rolling. The layer of oxide does not allow the lap to fuse during deformation and is manifested as a brittle fracture during drawing. [65]

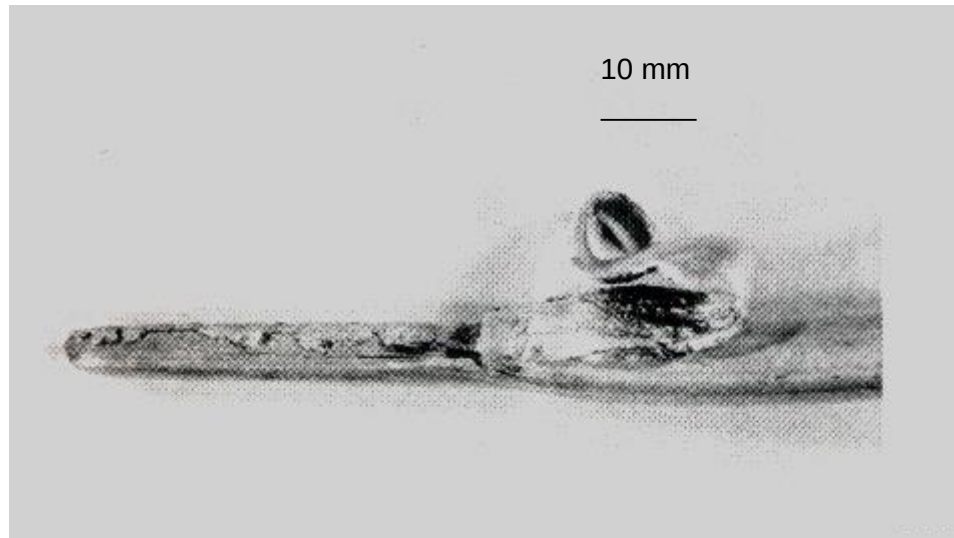


Figure 2.18 The sliver, showing characteristic “folded metal piece” is the result of an overfill. [75]

The sliver fracture is caused by various conditions that deviate from the normal processes. These include overfills(out of round) and surface cracks which occur during the hot-rolling process, guide scratching in the rolling mill, cast bar surface defects, and bar turnings which get caught in the mill and are rolled into the rod. The sliver fracture can be prevented by ensuring that the cast bar is free of copper shavings and surface cracks. [65]

2.9.9 Weld Breaks

Weld breaks are recognisable by their fish-mouth appearance . Brittleness is usually associated with this type of fracture in that the fracture surface reveals a coarse, granular structure. Experimental work reveals that the electrical current setting used in welding can induce oxygen into the weld zone. [65]

Causes for the weld break type of fracture include: foreign material, high concentration of copper oxide in the weld area, defective shearing blades, improper rod-end geometry, incomplete flash dressing of the rod, and improper current setting and/or welding pressure. The centre portion of the weld area contains grains which show significant grain growth. The absence of deformation twins and the irregularities of the grain boundaries indicate that these grains have been subjected to temperatures close to the melting point.

CHAPTER 3

EXPERIMENTAL PROCEDURE

The project involved the use of several different experimental techniques. Copper wire break samples, which occurred during industrial wire drawing processes, were received from the industrial sponsor (Samples were collected over a period of one year). The samples were examined using SEM with an EDS Analyser, and the causes of the wire breaks were thus determined. A classification and a statistical analysis of the wire breaks were produced.

For successful modelling of the wire drawing, input data was required from the laboratory scale experimental wire drawing apparatus. For this purpose it was necessary to produce material for wire drawing. So, first of all some extrudes were produced at different temperatures. Some of the extrudes were used for wire drawing and tensile tests after each reduction stage were performed to determine the work hardening exponent and K values. The results from these experiments were then used as input data for a finite element modelling package-Forge2. This package was used to simulate the wire drawing process and the major wire defects inclusion and macroporosity types of break.

The experimental techniques used in the project included:

- SEM Examination
- Extrusion
- Wire Drawing
- Tensile Testing
- Modelling of the Drawing Process

3.1 SEM Examination

The sponsoring company-Sarkuysan collected some copper wire break samples for a period of one year and sent these samples to Imperial College for SEM examination of the fracture surfaces. Some of the samples were also examined at Sarkuysan Company Laboratory. Break samples from the Imperial College wire drawing experiments were also examined. Both SEMS (JSM - T200 and JSM - T220A) at Imperial College and a SEM(Jeol 5600 with) at the Sponsoring Company-

Sarkuysan were used for examining these wire breaks by secondary and back scattered electron imaging. Additionally, the T200 and Jeol 5600(equipped with an Oxford Analyser) were also used for EDS analysis to determine the chemical analysis of the inclusions in the wire break samples. The samples had a diameter range between 5 mm and 0.1 mm. For this reason, two different sized sample holders were required. The samples were examined using magnifications from 50 to 400X and some representative micrographs were produced.

3.2 Experimental Wire Drawing

The feedstock for wire drawing was produced via hot extrusion of as-cast ETP-Cu. Prior to extrusion ETP-Cu was machined into 75-mm diameter x 85mm long cylindrical billets. The full chemical composition of ETP-Cu is given in Table 3.1.

S	Cd	Mn	Si	As	Pb	Ag	Bi
13 PPM	0.1 PPM	0.25 PPM	0.07 PPM	0.92 PPM	0.74 PPM	9.66 PPM	0.41 PPM
Sn	Zn	Fe	Sb	Al	Co	Cr	Ni
0.23 PPM	0.42 PPM	13.04 PPM	0.35 PPM	0.04 PPM	0.26 PPM	0.33 PPM	3.82 PPM
Se	Te	P	O ₂	H ₂			
1.15 PPM	0.33 PPM	5 PPM	492 PPM	1.8 PPM			

Table 3.1 Chemical Analysis of ETP-Cu.

The billets were heated to 850°C and extruded using an ENEFCO 5 MN hydraulic vertical press acting in the direct mode. A heated container (500°C) of 75-mm diameter was employed. The billet was extruded with a ram speed of 4 mm/sec through a flat faced die (7.76 mm diameter/extrusion ratio of 88:1). A graphite lubricant was applied to the tooling, and the extrude was water quenched upon emerging from the die.

The extruded copper rods (Diameter 7.76 mm) were cut into 50-cm lengths. These rods were used for mechanical property evaluation and in the wire drawing process. The wire was drawn in several stages as can be seen in Table 3.2.

Reduction Stage	Reduction($\ln D_1/D_2$)	Total Reduction($\ln D_0/D_2$)
7.76-7.13 mm	0.169	0.169
7.13-6.35 mm	0.232	0.401
6.35-5.79 mm	0.185	0.586
5.79-5.28 mm	0.184	0.770
5.28-4.76 mm	0.207	0.977
5.76-4.24 mm	0.232	1.209
4.24-3.70 mm	0.273	1.482

Table 3.2 True strain values for each wire drawing stage.

The geometry of the dies used during the wire drawing stage can be seen in Figure 3.2. It can be seen from the figure that, a reduction angle of 11° and bearing length of 30 % of the die diameter was used.

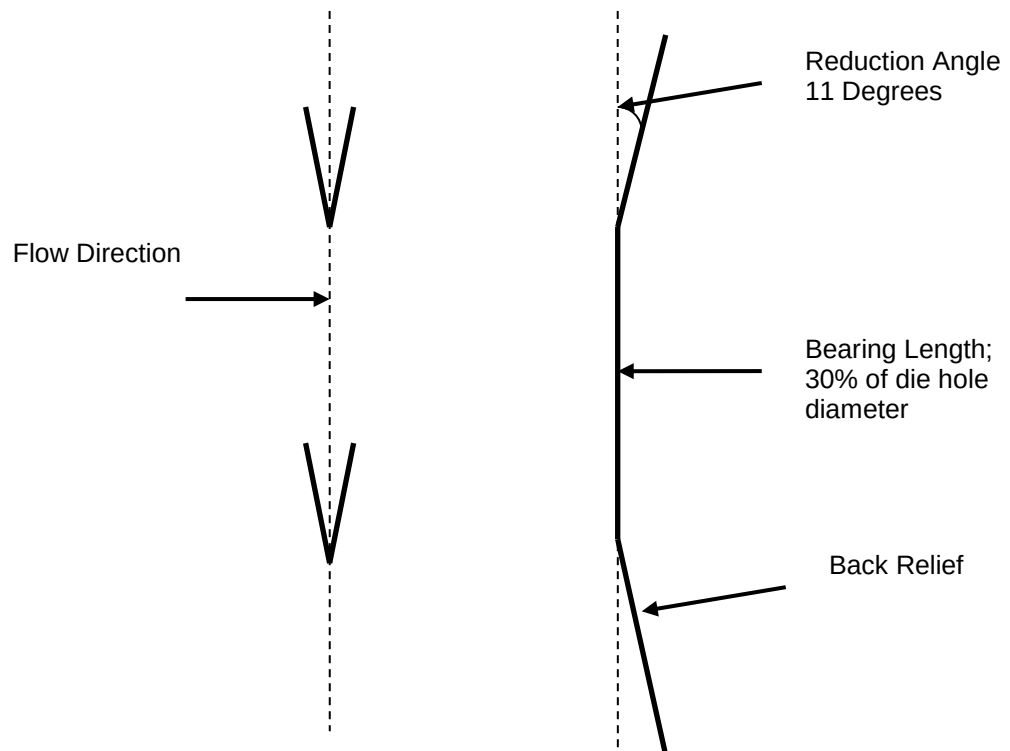


Figure 3.2 Die geometry of the dies used during the wire drawing process.

In order to facilitate the first stage of wire drawing the rods were pointed at one end so that they could go through the 7.13-mm die. This was done by a process known as swaging.

The wire drawing lubricant used (Lubricol 22G) is based on highly refined mineral oil, natural fatty oils, synthetic fats and alkaline surfactant emulsifiers. The addition of the soluble oil (10%) was made slowly to the water. Pure distilled water was used, because the quality of water is probably the most important factor influencing an emulsion's performance. This emulsion was added to the lubricating bath until the die was completely covered by it. (See Figure 3.3.)

A laboratory wire drawing machine was used with the drawing head moved by a chain drive. (As can be seen in Figure-3.3.) The optimum operating temperatures for drawing emulsions are between 35°C and 45°C. For this reason a heating element was used to ensure adequate lubricant temperature control.

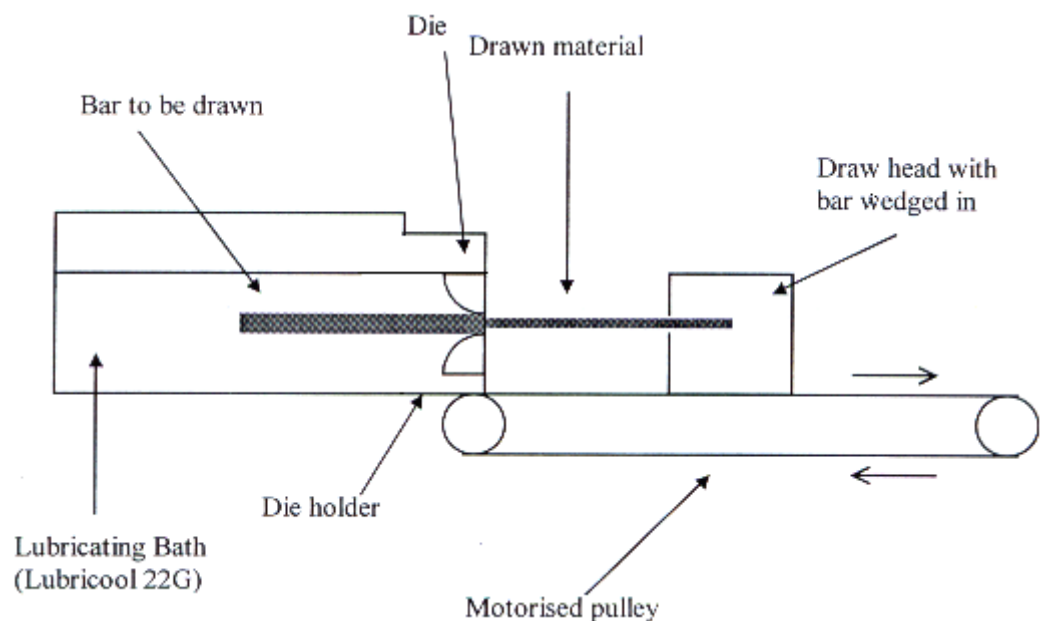


Figure 3.3 Drawing bench setup.

The pH value indicates the alkalinity or acidity of an emulsion and it was measured using a pH-meter. pH values below recommended levels (the pH value of a fresh emulsion-concentration 10%- is typically 8.5 - 8.8) could cause a reduction in detergency, emulsion instability and increase the risk of corrosion. pH adjustments were made by adding dilute caustic soda to the emulsion. High pH values are

unusual, but alkalinity is sometimes introduced as bicarbonates in the water supply, and it can lead to poor lubricity and foaming.

The computer was interfaced to the experimental wire drawing machine to record the load-displacement data. The swaged end of the rod was passed through the die and then attached to the draw head and the wire drawing process started.

3.3 FEM Model

The commercial software program Forge2 Transvalor SA was used for the modelling part of this project.[79]

Basically the Forge2 package can be divided into three sections; “Pre-Processing” where-by the program is set up for simulation, “Simulation” where the simulation is performed, and “Post-Processing” where the results are analysed.

Before the simulation can be carried out three files need to be created for the pre-processing;

- Data File,
- Mesh File,
- Tooling File.

The data file is a text file that gives all the relevant data that the simulation program needs in order to operate. This file is split into several modules:

- 1) Fichier is the module which gathers all the names of the files (meshing, tooling and output data file) used in the simulation.
- 2) Rhelogie is the module which gathers together the data defining the flow behaviour of the material and the friction conditions between the material and the tooling.
- 3) After a significant amount of simulated deformation remeshing is required to permit further deformation. Mayeur is the module which remeshes the material and transfers the relevant information from the old mesh to the new one.

The mesh file contains the information that relates to the initial dimensions of the material prior to deformation and the finite element mesh that is to be used. This is created by using a program called xmayeur.

The tooling file contains the dimensions of the tooling and defines the movement of the tools during deformation. This can be created by using a program called xcreout.

Once the data, mesh and tooling files have been defined the simulation can be performed by using a program called xforge2-axi-e. This program performs a 2D axisymmetric simulation using an elasto viscoplastic description of the material behaviour. The data is stored in the data file and is analysed during post-processing. Post-processing analysis allows the data files to be read and the results to be represented graphically.

3.3.1 Material Behaviour

The material was assumed to obey an elasto viscoplastic behaviour. As shown in Figure 3.3.

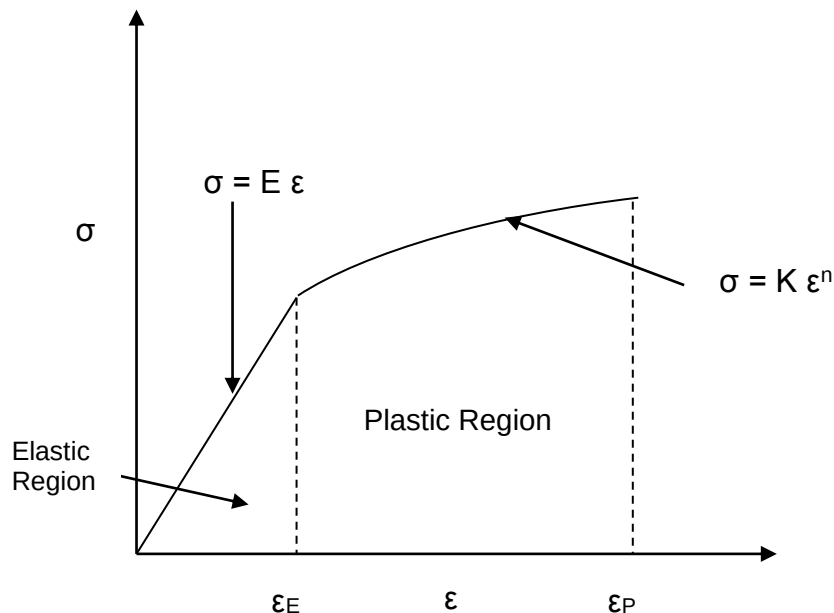


Figure 3.3 Schematic of the elasto viscoplastic behaviour.

In Figure 3.3 it can be seen that part of the deformation is represented by a reversible elastic behaviour (Elastic Region). The parameters defining the material's elastic behaviour are Young's Modulus (E) and Poisson's Ratio (ν). The values of E and ν are usually constant, but they can also depend on the temperature.

The plastic region of the deformation is represented by irreversible plastic behaviour. The material behaviour is idealized by the law of $\sigma = K \epsilon^n$. The parameters defining the material viscoplastic behaviour are the constant (K) and the coefficient of strain hardening (n).

The results from compression testing were used to provide data for the plastic behaviour of the material in order to obtain the constants K and n .

The first requirements in terms of input were values of the elastic modulus and Poisson's ratio for copper. These are given below;

Elastic Modulus = 110 GPa

Poisson's Ratio = 0.33

7.76 mm diameter X 10 mm samples were machined from the extruded bar. Compression tests were performed on a Servo Hydraulic 100 kN Mates Testing Machine at a constant strain rate of 10^{-2} s^{-1} . Lubrication was provided by PTFE tape. Regression of the plastic region of the stress strain curve provided the values for K and n .

$$\sigma = \sqrt{3} K \epsilon^n$$

$\epsilon < 0.4$ then $K = 270$ $n = 0.5$

$\epsilon > 0.4$ then $K = 210$ $n = 0.2$

As the process occurs at room temperature it is assumed that the material is strain rate independent and that negligible thermal variations occur during the process (isothermal conditions).

The friction shear stress (τ) is a fraction of the flow shear stress of the material. This value is defined through the friction coefficient (m).

$$\tau = 3^{1/2} m \sigma_0$$

For this work a value of 0.1 was used as friction coefficient.[52]

3.3.2 FEM Model Operation

The FEM of the wire drawing process was formulated using the axisymmetric elasto-viscoplastic version of the FORGE2 Version 2.7 modelling package by Transvalor SA of Sophia-Antipolis, France. The mesh geometry is represented below in Figure 3.4.

In FORGE2, the wire is made to pass through stationary dies. This can be achieved by defining a puller die attached to the front of the mesh. The mesh is made to stick to the puller die by the “contact bilateral” condition and this puller die is given a downward velocity. Dies were modelled according to the geometry in Figure 3.4. However, the die was defined without a back relief. It was found that the simulation could not run with a back relief defined in the die. As the mesh passes through the die the number of nodes in contact with the die changes periodically with displacement. This causes an oscillation in the friction conditions and thus the drawing load.

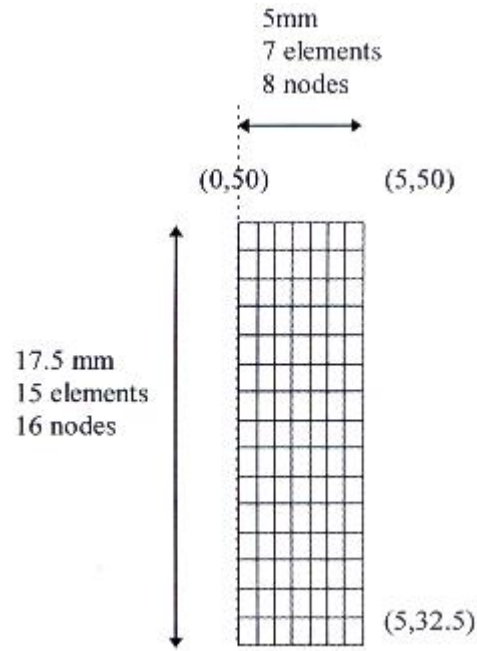


Figure 3.4 A general view of wire mesh.

In the computer model there are several variables that are listed below:

m-barre	= Friction Factor
n	= Work Hardening Exponent
K	= Constant
α	= Die Angle
d_{wire}	= Exit Diameter
Mesh Size	= (e.g. 5X20, 10X40, 20X80)
Bearing Length	= % of Die Diameter

Some of the above variables were varied in a sensitivity analysis, in order to establish their effect on the drawing load.

CHAPTER 4**EXPERIMENTAL RESULTS AND DISCUSSION****4.1 SEM Examination of Wire Breaks**

In total 4260 industrial wire break samples were examined using SEM and EDS. From these examinations the wire breaks were classified into 7 major groups. The distribution is shown in Table 4.1. The reader is referred to Section 2.9.1 for definitions of the different types of break. In Table 4.1, a general classification of the wire breaks is given with causes.

Type of Wire Break	%	Reason
Inclusions	35.3	Wire Drawing Practice (Wear of the dies or guide roles) or Material Quality (Wear of rolling mills, refractories, etc.)
V Shape Defect (Checked Wire)	23.3	Wire Drawing Practice (Improper die geometry) or Material Quality (Cracks on surface of the wire)
Tension Break	15.5	Wire Drawing Practice (Insufficient reduction, variation of drawing speed, etc.)
Macroporosity	10.1	Material Quality(Improper Solidification, insufficient liquid metal level in casting wheel)
Split End	7.3	Material Quality(Cracks in rod)
Wire Drawing Practices(W.D.P)	5.0	Improper wire drawing practices such as insufficient lubrication, die misalignment, weld breaks, etc.
Central Burst	3.5	Wire Drawing Practice(Insufficient Lubrication, Improper die geometry, etc.) or Material Quality(Local high concentration of oxygen)
Total	100	

Table 4.1 The classification of the wire breaks with causes.

Inclusions, V Shape Defect, Tension Break and Macroporosity were the major wire break types investigated. Split End, W.D.P. and Central Burst breaks are of secondary importance.

It is possible to compare these results with other studies. In 1988 at Sumitomo-Japan, it was found that more than 50% of the total wire breaks were inclusion breaks. [77] Another study which was made at Prescott Rod Rollers, England, determined that 52.8% of the total breaks were related to inclusions [80]. In 1993, at Southwire-USA, 70% of the total wire breaks were classified as inclusion breaks. [81]

When these results are compared with the figures in the present study (Table-1), it can be seen that once again inclusion breaks are the major break type, but their percentage(35.3%) is less than the literature figures. The figures mentioned in the literature are the wire breaks which occurred during the production of ETP-Cu wire, but in this project wire breaks which occurred during the production of OF-Cu wire are also included. In Table 4.3 if inclusion related breaks of ETP-Cu only are considered, this would be around 47% of the total wire breaks. This ratio is similar to the literature value. It was not possible to find in the literature, a study of OF-Cu breaks.

4.1.1 Statistical Analysis of Wire Breaks

A detailed classification of the wire breaks for different plants is given in Table 4.2. In the table, Rod to Fine breaks are the breaks which occurred in rod, thick, thin and fine wire drawing machines i.e. in those machines used to reduce the wire diameter down to Ø1.0 mm. Multiwire breaks are the breaks which occurred in Multiwire Drawing Plants and these machines can be fed with more than one basket at one time(Usually 8 to 24 wires can be drawn at the same time on the same machine to reduce the wire down to 0.10-0.25 mm). Superfine breaks are breaks which occur in Superfine Drawing Plants where relatively thinner sizes are drawn. (Ø0.05-0.16 mm)

Type of Wire Break	Rod to Fine Breaks		Multiwire Breaks		Superfine Breaks		Total Breaks	
	Number of Breaks	%	Number of Breaks	%	Number of Breaks	%	Number of Breaks	%
Inclusions	403	30.9	787	36.2	313	39.4	1503	35.3
V Shape Defect	243	18.6	544	25.4	207	26.0	994	23.3
Tension Break	189	14.5	255	11.8	216	27.1	660	15.5
Macroporosity	151	11.6	276	12.8	1	0.1	428	10.1
Split End	181	13.9	117	5.4	12	1.5	310	7.3
W.D.P.	77	5.9	91	4.2	44	5.5	212	5.0
Central Burst	60	4.6	90	4.2	3	0.4	153	3.5
Total	1304	100	2160	100	796	100	4260	100

Table 4.2 Wire break classification for each type of wire drawing plant.

As can be seen in Table 4.2 for all the wire drawing plants the most important type of wire break is that due to inclusions.

Sometimes it was not possible to determine the cause of the wire break by looking at the surface using SEM. For this reason it was necessary to also use EDS analysis, oxygen content analysis, full chemical analysis, and microstructure characterisation to determine the cause.

Type of Wire Break	Insufficient Material Quality (%)		Improper W.D.P. (%)	Total (%)
	ETP-Cu	OF-Cu		
Inclusions	18.2	2.1	15.0	35.3
V Shape Defect	5.3	18.0	-	23.3
Tension Break	-	-	15.5	15.5
Macroporosity	7.3	2.8	-	10.1
Split End	2.0	5.3	-	7.3
W.D.P.	-	-	5.0	5.0
Central Burst	1.0	-	2.5	3.5
Total	33.8	28.2	38.0	100

Table 4.3 Classification of the wire breaks according to the source material.

In Table 4.3. the wire breaks are divided into three different categories; Insufficient Material Quality for ETP-Cu, OF-Cu and Improper Wire Drawing Practices. As can be seen 33.8 % of the total wire breaks originate due to insufficient material quality in ETP-Cu, 28.2% originate due to insufficient material quality in OF-Cu and 38.0 %, originate due to improper wire drawing practices.

Inclusion breaks are the most important type of break in ETP-Cu and also in Improper W.D.P. In OF-Cu, V Shape Defect and Macroporosity are the most significant types and it is believed that both types of break originate for the same reason. It is well known that when the solidification process is unsatisfactory, Macroporosity breaks occur. If the porosity is small and close to the wire surface, the resultant wire break could be a V Shape type of failure. At some stage of wire drawing, porosity comes very close to the surface, and the V shape wire defect failure occurs. 38.0% of the total wire breaks originate because of improper W.D.P. and the Inclusion type of break is the highest contributor in that group.

Figures 4.1-4.3 show the distribution of the wire breaks according to the wire break diameter for each wire drawing plant.

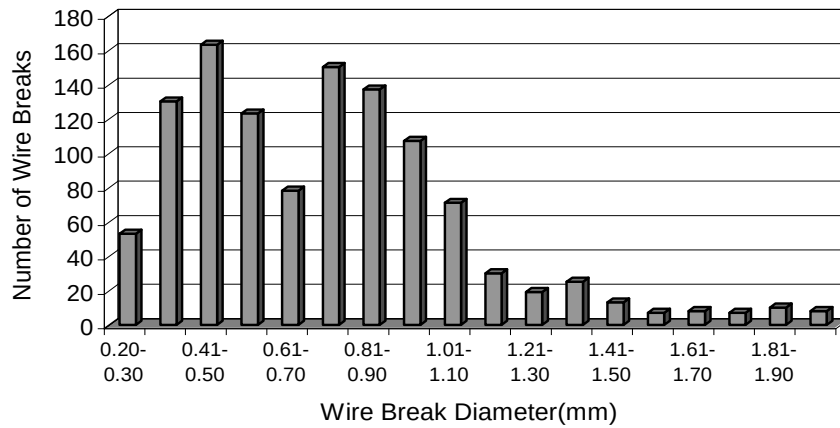


Figure 4.1 Distribution of the wire breaks according to their break diameter for Rod to Fine Breaks.

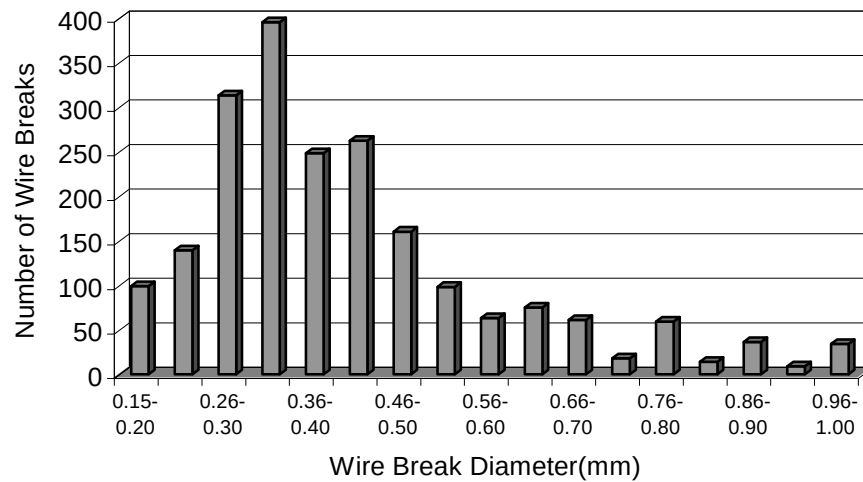


Figure 4.2 Distribution of the wire breaks according to their break diameter for Multiwire Breaks.

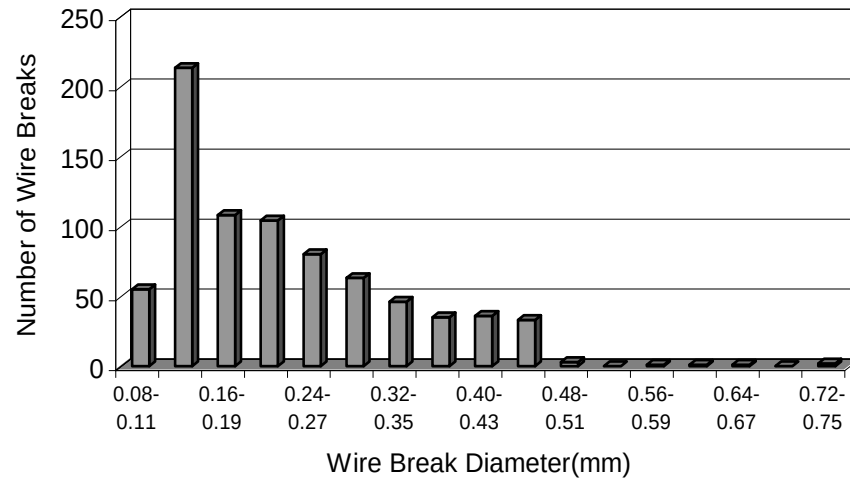


Figure 4.3 Distribution of the wire breaks according to their break diameter for Superfine Breaks.

As can be seen from these graphs the wire break occurrence reaches a maximum value for a particular diameter range.

Rod to fine breaks (Figure 4.1) start to increase for the wire diameter range 1.11-1.20 mm. After that size band the wire break frequency increases significantly as the wire break diameter decreases. The peak size bands are 0.71-0.80 mm and 0.41-0.50 mm. It can be concluded that 85% of total wire breaks occur in wires with diameters greater than 0.41 mm.

Multiwire breaks, which are the most significant wire break type (Figure 4.2), start to increase for the diameter range 0.66-0.70 mm. After that size band the wire break frequency dramatically increases as the wire break diameter decreases. It reaches a peak value when the size band is 0.31-0.35 mm. It can be concluded that 85% of the total wire breaks occur in wires with diameters greater than 0.30 mm.

The occurrence of superfine breaks (Figure 4.3), starts to increase for the diameter range 0.44-0.47 mm. After that point the frequency of wire breaks increases significantly and it reaches a peak value for the 0.12-0.15 mm band. 85% of the total wire breaks occur in wires with diameters greater than 0.14 mm.

As a result, it can be concluded that 85% of the total wire breaks occur in wires with diameters greater than 0.41mm at the Rod to Fine stage. The corresponding diameters for the multiwire and superfine wire stages are 0.3 mm and 0.14 mm respectively.

4.1.2 SEM Studies

Examples of the SEM micrographs obtained from the wire breaks can be seen in Figures 4.4-4.8.

The wire breaks which occurred during the final reduction to 3.70 mm in the laboratory were also examined by SEM. This type was identified as a tensile break. The SEM photograph in Figure 2.17 shows a typical example.

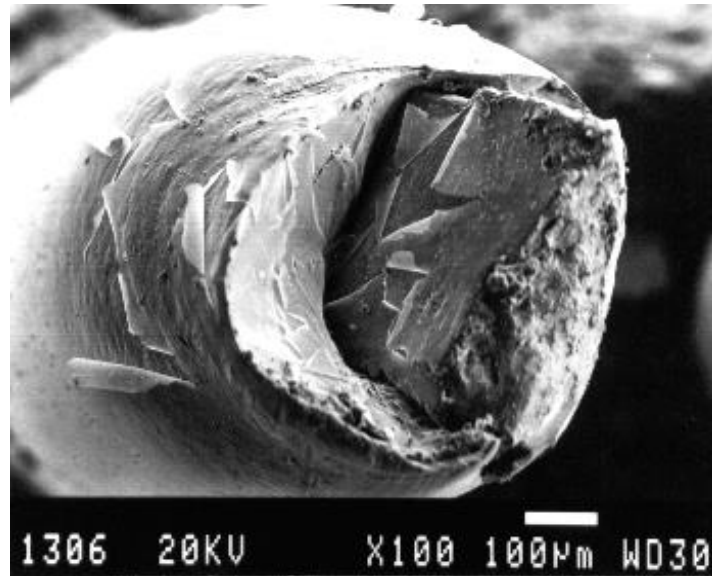


Figure 4.4 Inclusion Break; Micrograph of a wire break (Diameter of Wire:0.98mm) exhibiting a fracture induced by the presence of an FeCr5% inclusion which was introduced during the rolling of the bar in SCR-Southwire Continuous Casting Plant.(Rolling Mill Material; DIN-2344)

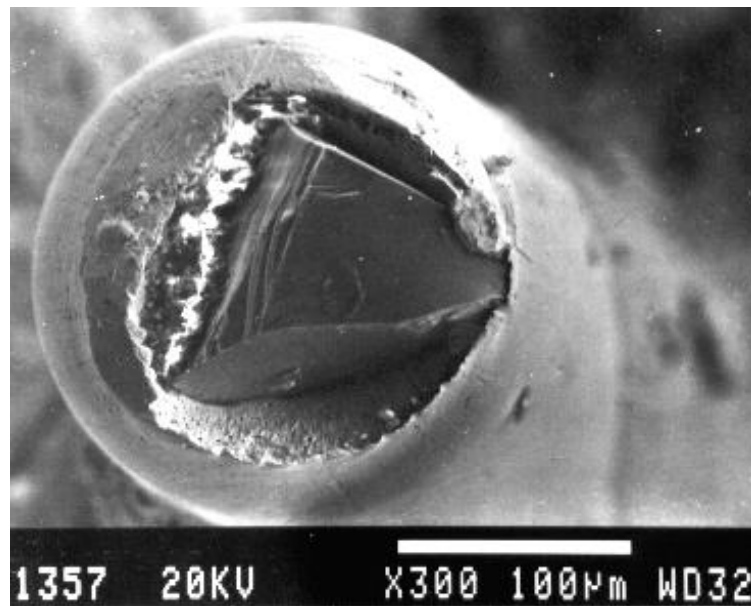


Figure 4.5 Inclusion Break; Micrograph of a wire break (Diameter of wire: 0.28 mm) exhibiting a fracture induced by the presence of a Si inclusion which was introduced during the melting of copper in SCR-Southwire Continuous Casting Plant.(Refractory Material; SiC)

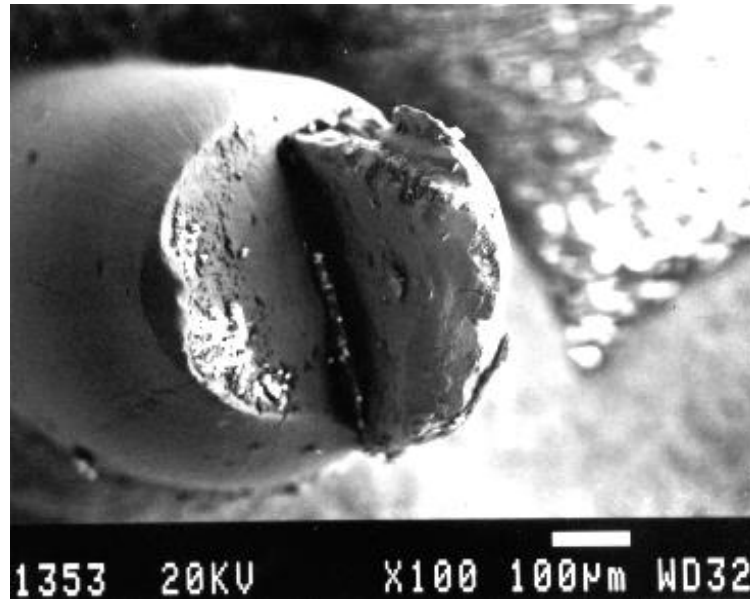


Figure 4.6 Inclusion Break; Micrograph of a wire break (Diameter of wire: 0.60 mm) exhibiting a fracture induced by the presence of an Fe inclusion which was introduced during the wire drawing operation .(Entrance guide roll; Low Carbon Steel)

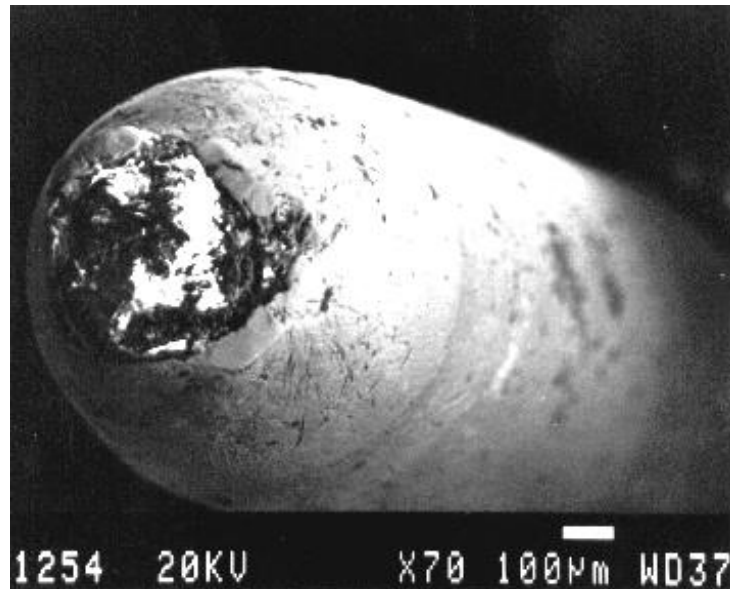


Figure 4.7 Micrograph of a tensile-type break.(Diameter of wire:1.08 mm)

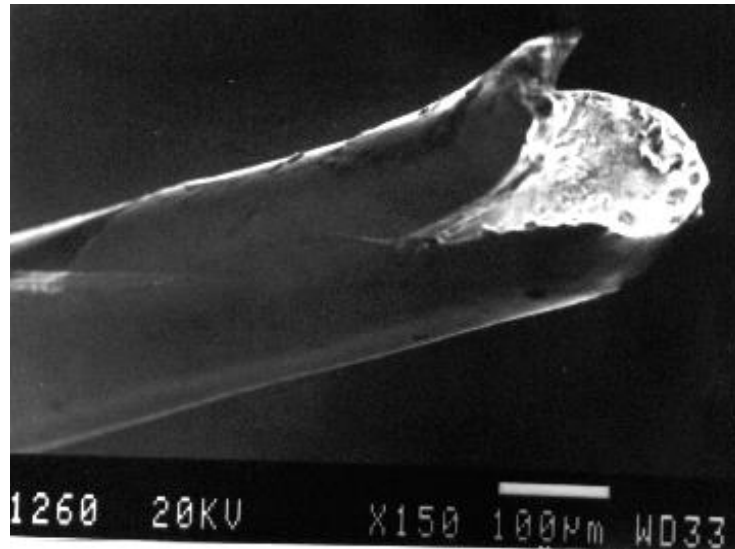


Figure 4.8 Micrograph of a split end wire failure.(Diameter of wire:0.26 mm)

4.1.3 Inclusion Breaks

Inclusion break surface examinations need to be supported with EDS analysis to determine the chemical composition of the inclusion. If the inclusion has fallen out of the SEM specimen, then it is impossible to determine the source of the inclusion. After the determination of the chemical composition of the inclusion, the source can be readily ascertained.

After the elemental analysis, the form of the elements (alloyed or unalloyed) which were detected has to be identified. For this purpose image analysis was used and with the help of this method the location of the inclusion on the wire break surface and the form of the elements were determined. On the wire break surface elements were analysed separately, and for each element a different map was developed. (Figure 4.14-16)

4.1.3.1 Statistical Analysis of Inclusion Breaks

In Table 4.4 the inclusion related wire breaks are classified according to the composition of the inclusions involved.

Inclusion Composition	Percentage of Total Inclusion Wire Breaks(%)	Inclusion Type
Low Carbon Steel(Fe)	47.1	Magnetic
FeCr5%(DIN 2344)	43.0	Magnetic
Silicon(Si)	6.4	Non-Magnetic(Refractory)
FeCr12%(2379)	2.3	Magnetic
Alumina	0.6	Non-Magnetic(Refractory)
Nickel-Phosphorus	0.6	Non-Magnetic(Refractory)

Table 4.4 Inclusion classification of the inclusion related wire breaks.

It was found that iron (Figure 4.6.) and FeCr5%(Figure 4.4) inclusions contribute 90.1% of the total inclusion related breaks. Fe inclusions originate from the entrance guide roles of the wire drawing machines and FeCr5% inclusions originate from the roll material in the mill used to roll from bar form (trapezoidal) to rod form(8mm) at the SCR Plant.

FeCr12% inclusions originate from the roll material in the Vals Machine (used to reduce the 20 mm Outokumpu OF product to 8mm rod). Si,(Figure 4.5) Al and NiP inclusions come from the refractory materials which are used in the furnaces at SCR and Outokumpu Plants. The refractory inclusion total is 7.6%.

These results indicate that it can be concluded that 70% of the total inclusion related wire breaks occur in wire diameters below 0.4 mm (Figure 4.9). From these results the sensitivity of the Ferromat device in the SCR Continuous Casting Plant and at the Wire Drawing Machines should be set to detect inclusions in this size range.

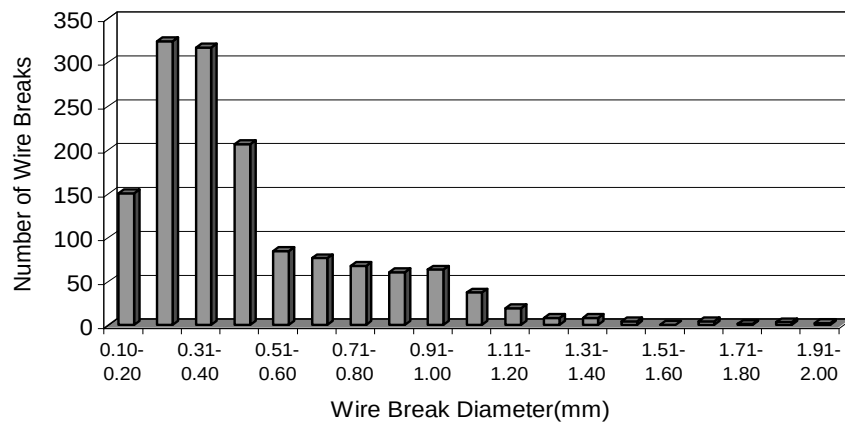


Figure 4.9 Wire break diameter distribution for the inclusion-related breaks.

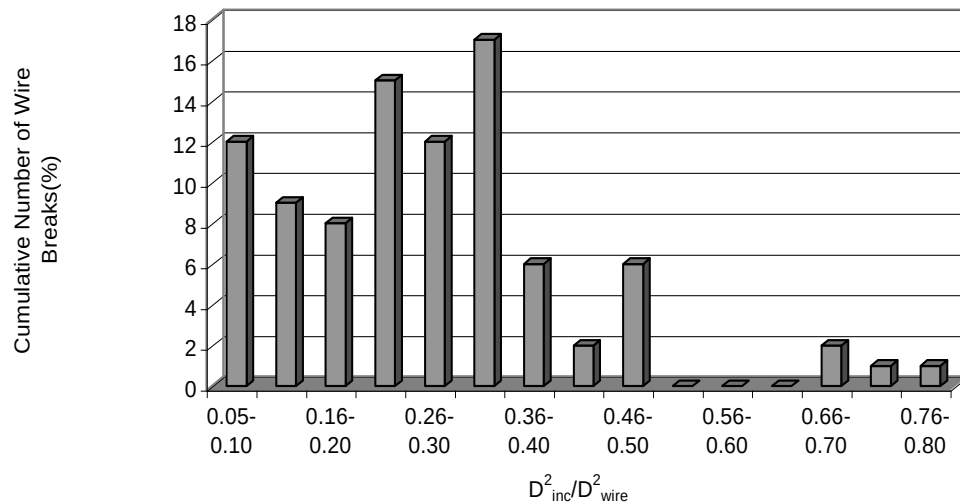


Figure 4.10 Distribution of inclusion-related breaks according to the ratio of D^2_{inc}/D^2_{wire} .

In Figure 4.10 the effect of the ratio of D^2_{inc}/D^2_{wire} is analysed and it is found that 85% of the total breaks occur when the ratio is ≤ 0.4 . The dependence is particularly sensitive in the D^2_{inc}/D^2_{wire} ratio range of 0.21-0.35.

As can be seen from Table 4.4, low carbon steel, FeCr5%, and silicon are the major inclusion types. When these inclusion types are examined carefully, the following results are obtained:

Low carbon steel inclusion related breaks occur in larger wire diameters compared to FeCr5% and silicon related inclusion breaks. Silicon related breaks occur in smaller diameter wires than low carbon steel and FeCr5% inclusion related breaks.

In summary the most detrimental inclusion type is low carbon steel followed by FeCr5% and then silicon (Low carbon steel inclusions cause wire breaks at an earlier stage in the process because of their larger sizes).

4.1.3.2 EDS and Image Analysis of Inclusions

EDS analysis results can be seen in Figures 4.11 to 4.13 for the three major inclusion types, (Fe, FeCr5% and Si inclusions) and by using this method the analysis of the chemical composition of the wire break surface was determined via the peak energy values.

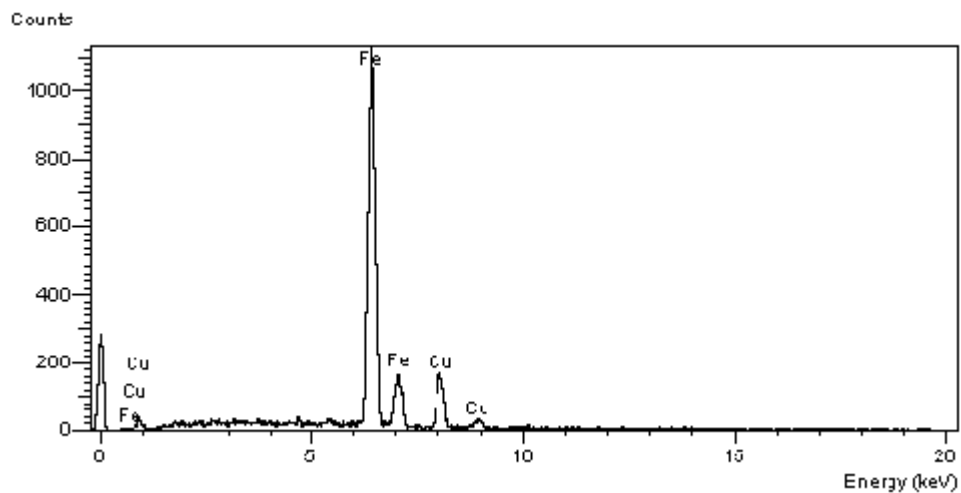


Figure 4.11 EDS Analysis result for a wire break surface which has an iron inclusion

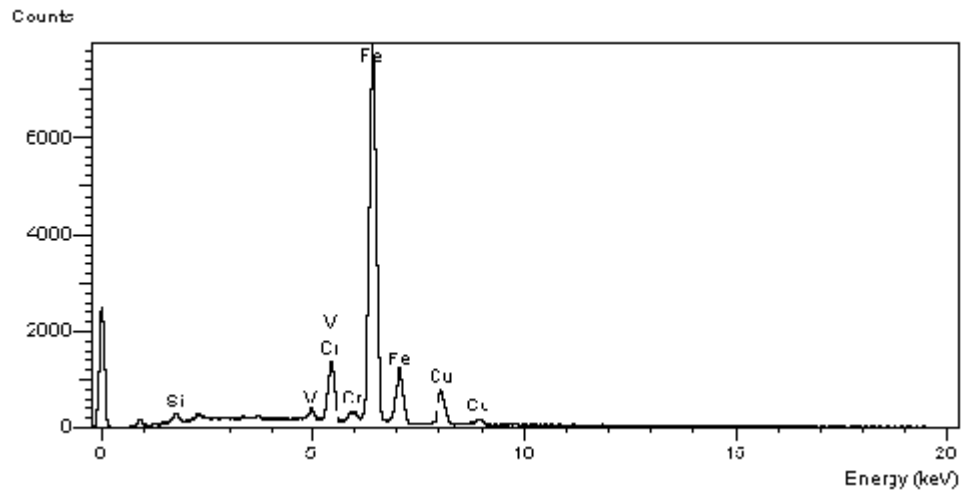


Figure 4.12 EDS Analysis result for a wire break surface which has an FeCr5% inclusion.

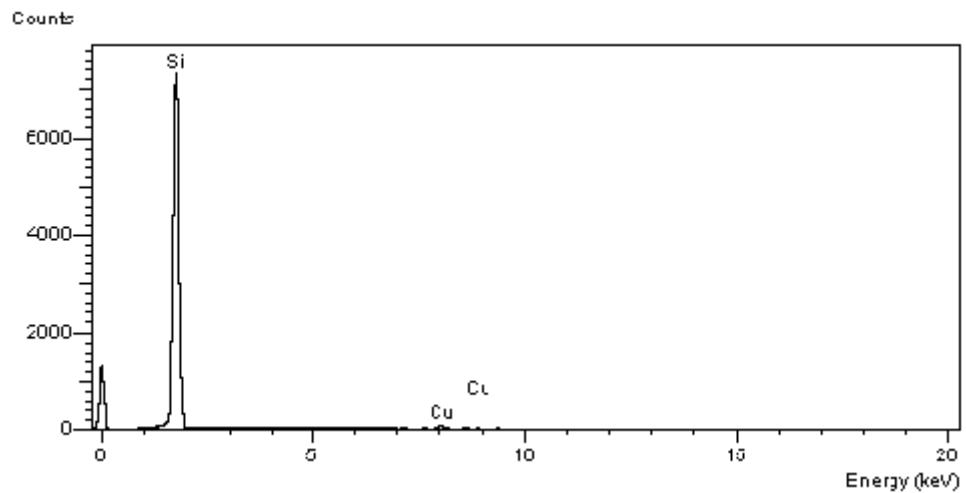


Figure 4.13 EDS Analysis result for a wire break surface which has a Si inclusion.

In Figure 4.14. the image analysis of an iron inclusion is shown. Figure 4.14.b. shows the iron inclusion alone and Figure 4.14.a. shows the wire break surface with the inclusion.

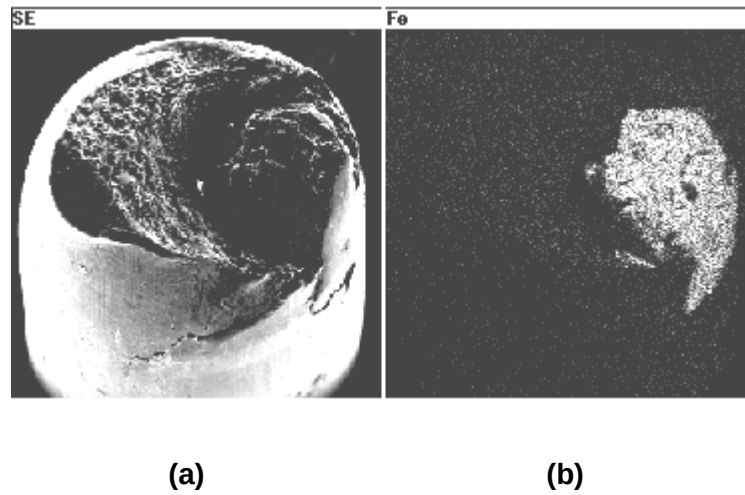


Figure 4.14 Image analysis of iron inclusion on the wire break surface(200X).

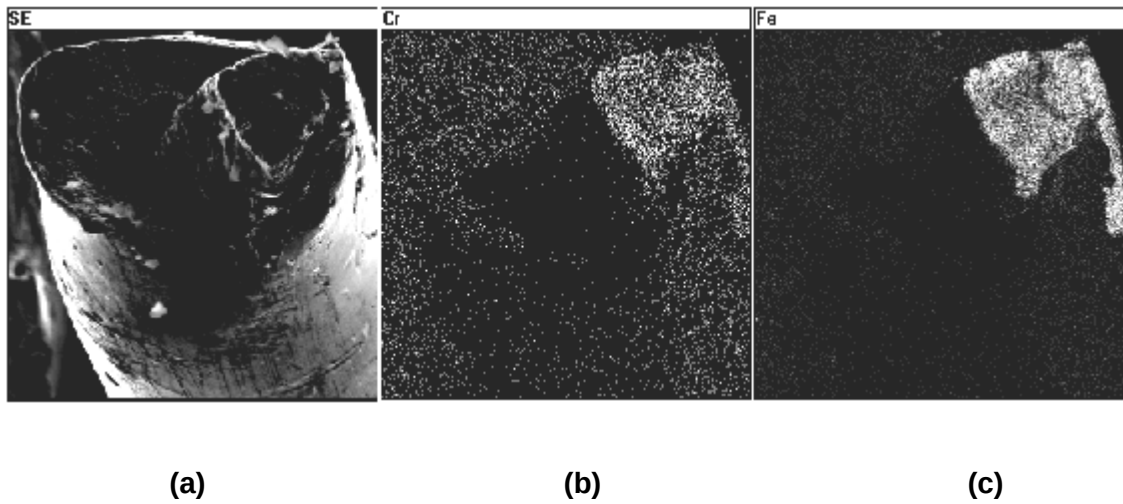


Figure 4.15 Image analysis of FeCr5% inclusion on the wire break surface(300).

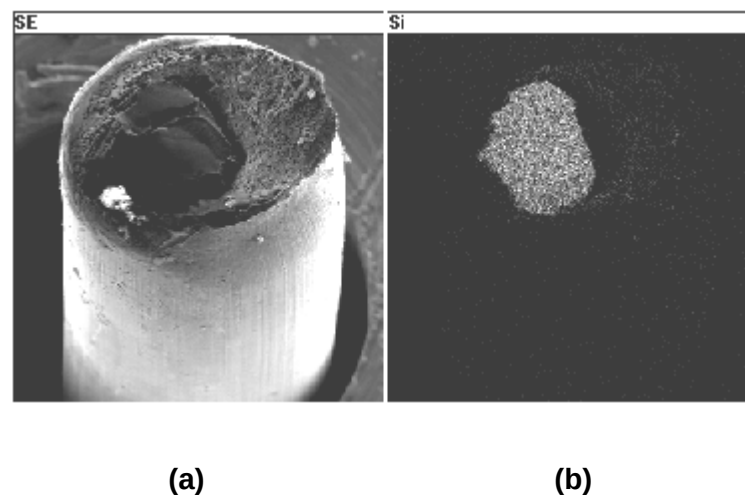


Figure 4.16 Image analysis of Si inclusion on the wire break surface(250).

In Figure 4.15 the image analysis of an FeCr5% alloy inclusion (DIN 2344 hot working steel) can be seen. Fe and Cr elements were detected in the same area and this indicated that these materials are in alloy form.

In Figure 4.16 the image analysis of a Si inclusion is shown. This Si inclusion comes from the refractory materials and it is believed to exist as SiC. However it was not possible to detect carbon with the existing EDS system.

4.1.4 Macroporosity Breaks

Macroporosity breaks constitute 10.1% of the total wire breaks, (Table 4.4.) and are thus very important. Macroporosity breaks are very significant at the Multiwire Drawing Plant. From Table 4.3, it was determined that Macroporosity plus V Shape defect breaks, which originate in OF-Cu, constitute 20.8% of the total breaks.

This type of break generally occurs because of unsatisfactory solidification conditions in the Continuous Casting Plants. The cavities which cause this macroporosity break can be formed during casting, either by excessive gas in the molten metal or by solidification shrinkage in the centre of the casting. During casting of copper, insufficient feeding of liquid metal into the mold (rotating casting wheel) can create porosity problems inside the metal. (Figure 4.17)

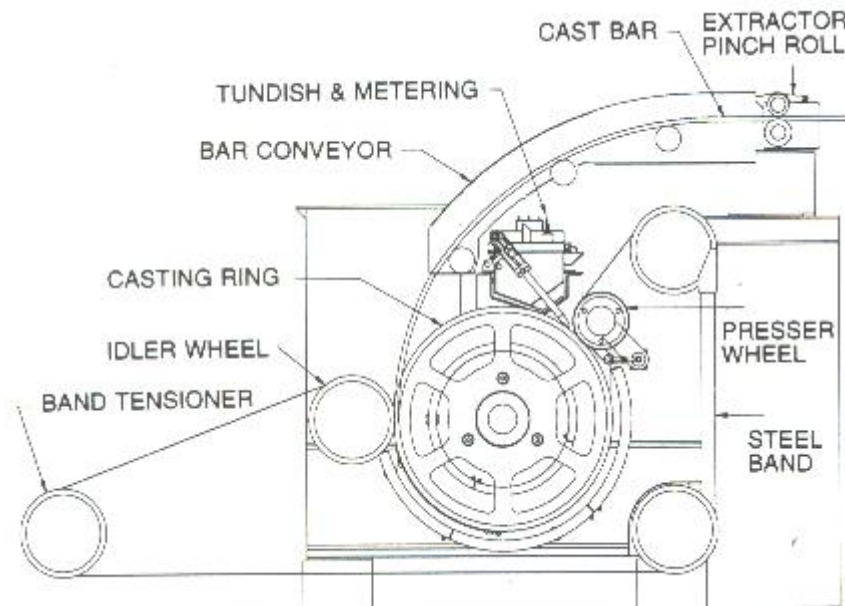


Figure 4.17. Schematic of SCR casting machine.

Macroporosity can be prevented by several methods which include casting copper without excessive gas content, and providing sufficient cooling during the early stages of solidification to avoid a molten centre when the casting leaves the wheel.

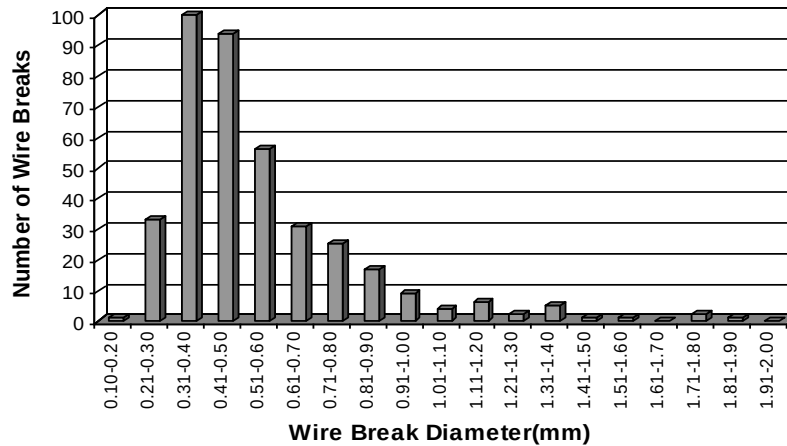


Figure 4.18 Wire break diameter distribution for the macroporosity breaks.

Figure 4.18 shows that most of the Macroporosity breaks occur in the range of 0.31-0.50 mm.

4.1.5 V Shape Defects

Another major wire break type is the V Shape which constitutes 23.3 % of the total wire breaks (Table 4.4). In Rod to Fine Breaks and Multiwire Breaks, it is the second most important type of break and in Superfine Breaks, it is the third most important type. Most V Shape Defects originate in OF-Cu(18.0 %) and the remainder in ETP-Cu(5.3%). Although the causes of V Shape Defects can be due to either material quality or wire drawing practise, in this investigation all examples of this type of break originated from poor material quality. Failure initiates at surface checks(Checked Wire) which are crack initiation points. The checks could originate due to physical abuse, poor die geometry, die misalignment (Wire Drawing Process Defect) or a localised high oxygen concentration on the wire surface as a result of a high oxygen content in the as cast-rolled surface bar. (Material Defect for ETP-Cu).(Figure 2.14)

The wire is brittle and can be broken easily when bent at one of the check marks. The impurities, mostly cuprous oxide, are the result of the original surface of the cast-rolled bar. If excessive amounts of non-ductile segregated material are present

or, if excessive oxygen is present, the resultant rod is susceptible to checking. For this reason, checked wire is rare in continuous cast rod except when excessive amounts of oxygen are present. Oxygen amounts in excess of 600 PPM will have a greater tendency to create “stringers” of oxides which may then lead to a fracture. In OF-Cu, V Shape Defect failures generally originate at small pores which are very close to the surface of the wire.

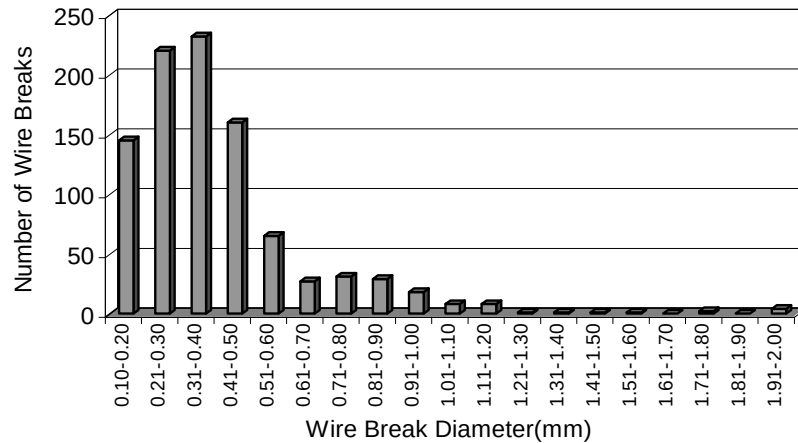


Figure 4.19 Wire break diameter distribution for V Shape Defect breaks.

Figure 4.19, shows that most of the V Shape Defects are in the wire diameter range of 0.21-0.40 mm. This defect begins to show up significantly when the reduction diameter reaches 0.60 mm.

4.1.6 Tension Breaks

15.5 % of the total wire breaks are Tension Breaks and the cause is improper wire drawing conditions.(Table 4.1.) This type of break is very common in Superfine Drawing constituting 27.1 %(Second most important wire break type).

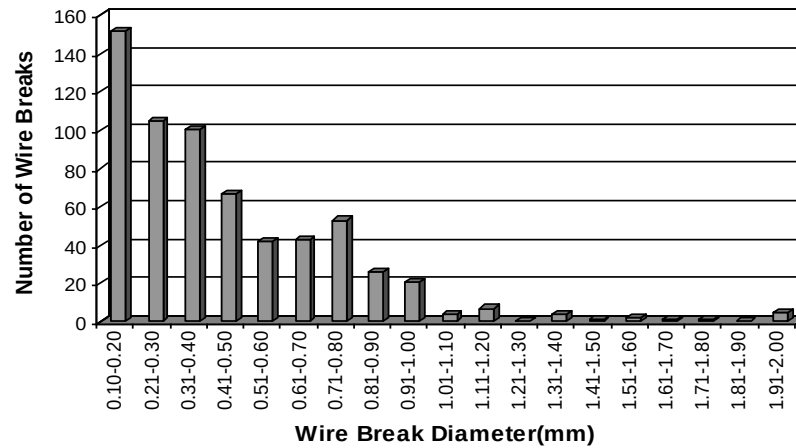


Figure 4.20 Wire break diameter distribution for the Tension Breaks.

The number of Tension Breaks increases as the reduction diameter decreases and it reaches a maximum value in the range of 0.10-0.20 mm.(Figure 4.20) As the wire diameter is reduced, the wire drawing parameters become more critical because of deformation hardening and associated reduction in plasticity. In addition small copper particles (fines) can become trapped in the die entrance, preventing smooth passage of the wire.

4.1.7 Split End

Split End breaks are responsible for 7.3 % of the total wire breaks. They are very significant in large wire diameter. 5.3 % of split end breaks occur in OF-Cu and the rest, 2.0 %, occur in ETP-Cu.

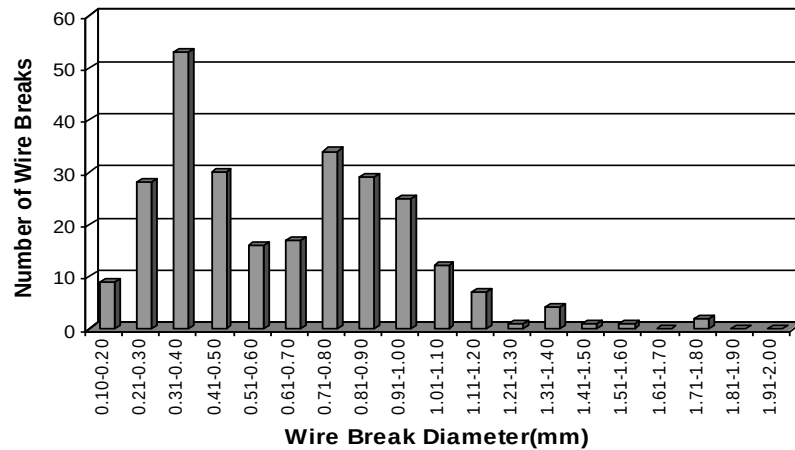


Figure 4.21 Wire break diameter distribution for the Split End breaks.

As can be seen from Figure 4.21 Split End breaks start to show up when the reduction diameter reaches 1.0 mm and the maximum value range is 0.31-0.40 mm.

This type of break develops a large crack resulting in a split in the middle of the wire.(Figure 4.8) The causes are :

- 1) Presence of a heavy copper oxide slag in the cast bar which is rolled into the rod.(Material Defect)
- 2) High concentration of copper oxide particles in the cast bar which remain undistributed resulting in a rod with a brittle centre and oxide stringers. (Material Defect)
- 3) Introduction of a foreign substance during the casting operation or prior to the rolling operation.(Material Defect)
- 4) Introduction of rolled-in copper oxide prior to the rolling operation.(Material Defect)

4.1.8 Improper Wire Drawing Practices(W.D.P.)

This type constitutes 5 % of the total wire breaks. Generally the broken surfaces do not have a specific geometric shape. The causes of this kind of break are; improper welding of copper wire, insufficient lubrication, die misalignment, improper die reduction, etc.

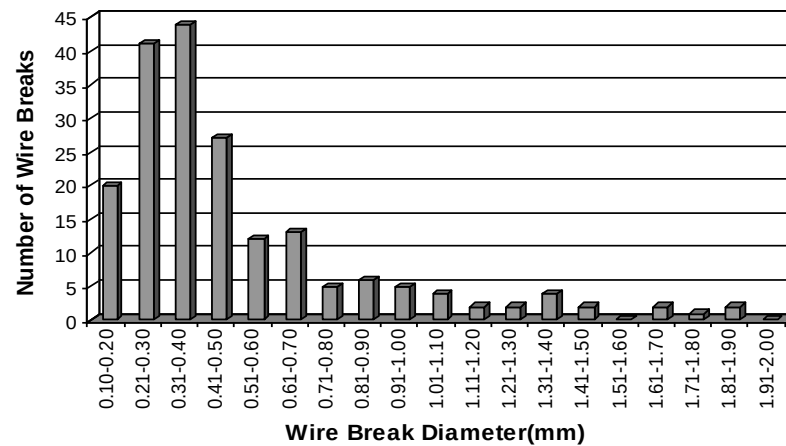


Figure 4.22 Wire break diameter distribution for the W.D.P. breaks.

As can be seen from Figure 4.22, most of the W.D.P. breaks occur in the range 0.21-0.40 mm.

4.1.9 Central Burst

3.5 % of the total wire breaks are Central Burst type. The cause of 2.5 % is improper wire drawing practices and 1.0 % is because of high oxygen content.(Over 500 ppm)

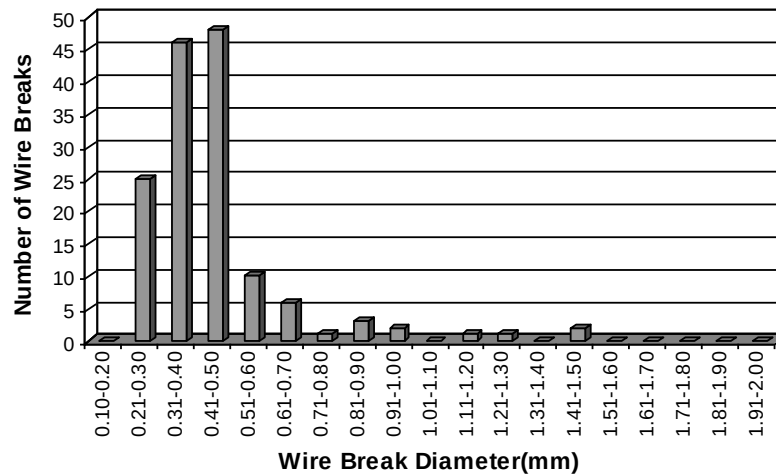


Figure 4.23 Wire break diameter distribution for Central Burst breaks.

As can be seen in Figure 4.23 most of the central burst breaks occur in the range 0.31-0.50 mm.

This type of wire break can have three different causes: (Figure 2.13)

1. High concentration of copper oxide particles or stringers in the central portion of the wire.(Material Defect)
2. Presence of a micro particle inclusion (magnetic or non-magnetic).(Material Defect or Wire Drawing Process Defect)
3. Improper die geometry, worn capstans, uneven entrance into a die, insufficient die lubrication or incorrect die reduction or entrance angle, excessively long land or bearing surface in the die.(Wire Drawing Process Defect)

Sometimes repeated central burst wire breaks can be observed during a wire drawing operation. If the oxygen level is higher than 450 PPM, then this can be the reason and it is probable that the Continuous Rod Production Plant is responsible for the high oxygen content and that more control is required during the production.(Material Defect) If the oxygen content is within the correct limits(180-450 PPM), then the wire drawing plant must check other factors such as die geometry, reduction, lubrication, etc.

4.1.10 Summary of Wire Break Investigation

In total 4260 industrial copper wire break samples were examined during this project and almost half of these wire breaks were “Inclusion” or “Macroporosity” in nature. Fine and superfine multiwire diameters are particularly susceptible to these kinds of breaks. As breaks at this stage of the drawing process cause the largest disruption the rest of the thesis will focus on these two causes of wire breaks.

Inclusion and macroporosity breaks can occur because of improper process conditions in continuous casting lines (SCR and Outokumpu), or improper process conditions during the wire drawing process. It was found that improper SCR and wire drawing process conditions are predominantly responsible for inclusion breaks: wire drawn from Outokumpu copper was found to be less susceptible to non ‘drawn-in’ inclusion breaks.

There was no discernable difference in the incidence of macroporosity breaks in copper produced from either of the casting routes. The reason for the higher number of inclusion breaks observed in the SCR copper rod can simply be explained in terms of the production method. In SCR the copper is cast and rolled to yield the feedstock for the drawing process, whilst Outokumpu copper feedstock is supplied in the as cast condition. In the latter process only refractory type inclusions are found, whilst in SCR copper inclusions derived from the rolling mills are also present.

Low carbon steel, FeCr5%, SiC, FeCr12%, Al_2O_3 and Ni-P were determined as the inclusion sources in this study. The majority of the inclusion breaks-(90% of total inclusion breaks) are related to ferrous based inclusions. 50% of inclusion breaks occurred in wires under 0.25 mm whilst 50% of macroporosity breaks occurred in wires under 0.35 mm.

In order to suggest methods for the control and prevention of inclusion breaks it is necessary to investigate each inclusion source separately.

Low Carbon Steel: The major source of inclusion breaks originated from low carbon steel and 50% of these breaks occurred in wires under 0.25 mm. The source of these types of inclusions is improper wire drawing process conditions. This is due to friction between the copper and entrance guides (constructed from

low carbon steel), causing the wire to pick up inclusions from the guides. These types of inclusions can be avoided by changing the material used for the entrance guides to a more wear resistant material. This can be achieved by using ceramic coated steel guides (TiC) or frictionless materials such as Teflon.

FeCr5%: Another major source of inclusion breaks originated from FeCr5% (a hot working tool steel), with 50% of these breaks occurring in wires less than 0.30 mm in diameter. This type of inclusion break is only observed in SCR produced material. The rolls used in the SCR process to hot roll copper from as-cast bar form (trapezoidal) to rod form (8mm Diameter Round Wire) are made from FeCr5% steel, and it is simply a wear process that leads to these inclusions being incorporated in to the wire. Increasing the frequency of roll change (12-24 hours), such that rolls are reground before major wear occurs, should lead to a reduction in the incidence of these breaks.

SiC, Al₂O₃, Ni-P: These three non-magnetic inclusion sources come from the refractory materials which are used in both continuous casting lines (SCR and Outokumpu). The refractory materials are used in the melting furnace, holding furnace, induction furnace and launders. Use of a filter in the casting pot and the regular control of the refractory (every six months the furnaces are emptied and visually inspected) can be effective in preventing this type of refractory inclusion.

FeCr12%: Another source of inclusion is the steel used for the cold rolls employed in the pre working of the Outokumpu feedstock from its as-cast 20mm diameter to 8mm suitable for wire drawing. As with FeCr5% inclusions, wear of the rolls is responsible for these inclusions. Whilst a more regular replacement of rolls could be beneficial, a more viable solution would be to modify the Outokumpu process to directly cast to an 8mm diameter rod using an up-cast method.

Macroporosity: Hydrogen porosity derives from the solidification process and is much harder to control. The amount of porosity is determined by the quality of the cathode feed stock, whilst the solidification rate controls the size. Both parameters are predetermined and are difficult to change. The SCR process incorporates a hot rolling stage in the production of the feedstock and, as a result, some porosity healing can occur. However by nature the rod rolling process does not lend itself to this. Whilst the Outokumpu process does not incorporate such a hot deformation stage, the initial as-cast diameter is smaller; hence a high cooling rate is achieved

leading to finer porosity. As a result no significant difference in the incidence of macroporosity breaks is observed between the two routes. It may be possible to improve matters by incorporating some form of inline degassing system, however the most realistic method is simply to improve the quality of the cathode feedstock and to take greater care over the operating conditions.

As a result of this investigation several improvements have been made to the production methodology employed at the sponsoring company's plant. These include, the introduction of ceramic coated steel guide rolls, more frequent roll changeover on the SCR line, and the introduction of a modified up-cast Outokumpu line directly casting to an 8mm diameter. The combined effect of these improvements has been to increase the average drawability on the multiwire lines from ~1000kg per break to over 5000kg per break.

It has been shown that several process improvements can be made to severely reduce the occurrence of wire breaks. However it is not feasible to eliminate inclusions altogether, and periodically wire breaks will occur. An alternative to prevention is detection. Several methods (e.g. eddy current) are already used industrially to detect inclusions prior to wire drawing. However these methods do have their limitations. There is a trade off between inclusion size and section thickness within which the inclusion can be detected. To detect a small inclusion only a thin section of rod (the surface layer) can be screened. Prior to wire drawing this type of screening is limited to detecting larger surface inclusions, and smaller central inclusions are not generally detected. What would be useful is a knowledge of critical inclusion size for a particular final wire diameter (i.e. the maximum defect size allowable for a break free wire). Once known it would be possible to place detection systems at strategic locations throughout the drawing plant, each detector set at a frequency to detect these inclusions. In the larger wire diameters the finer inclusions would not hinder the wire drawing process and therefore the detection systems could be set at low frequencies to detect the larger critical inclusions through the whole section of the wire. As the wire is drawn down the frequency of the detection systems can be increased to detect finer inclusions; as the section thickness is reduced detection across the whole wire diameter is possible.

The following sections will be devoted to analysing the results of the wire break investigations with the aim of developing a relationship between defect size/type and the minimum diameter to which a wire can be drawn.

4.1.11. Drawing Stress Analysis

It is known that failure in defect free wire drawing occurs when the drawing stress (σ_d) exceeds the flow stress (σ_y) of the wire. The exiting wire transmits the stress required for the drawing operation. If the drawing stress exceeds the stress that the wire can transmit (i.e. the yield stress) then the wire will break:

$$\sigma_d > \sigma_y \quad (1)$$

When there is a defect inside the wire, this equation has to be modified, as (assuming no transmission of stress through the defect) it will only be the material around the defect that will transmit the stress. In this case equation (1) becomes:

$$\sigma_d A_w > \sigma_y A_{eff} \quad (2)$$

Where A_w is the cross sectional area of the wire and A_{eff} is the effective cross sectional area of the wire (i.e. the wire section transmitting the drawing stress):

$$A_{eff} = A_w - A_{def} \quad (3)$$

Where A_{def} is the cross sectional area of the defect. (Figure 4.24).

Equation 2 becomes:

$$\sigma_d A_w / (A_w - A_{def}) > \sigma_y \quad (4)$$

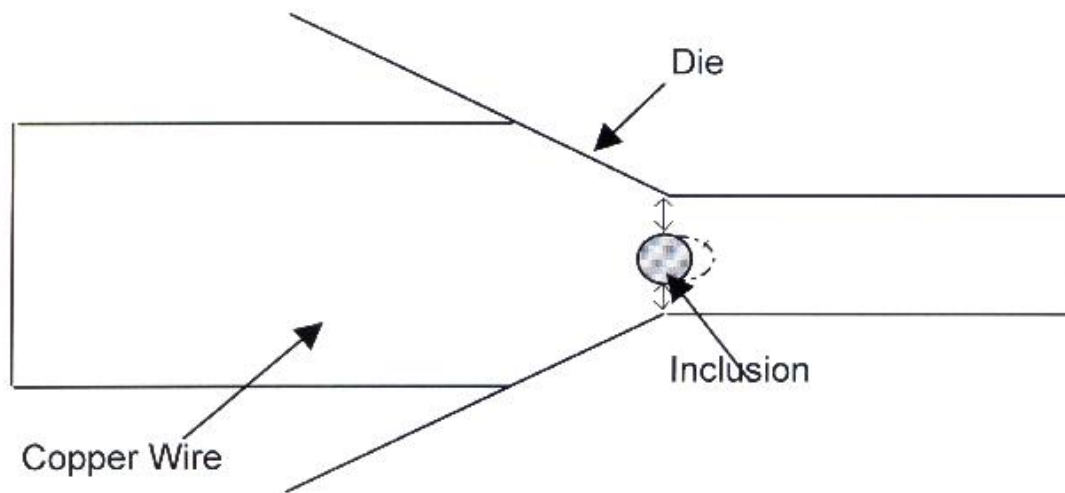


Figure 4.24. Schematic of a wire drawing process with an inclusion inside.

Hence the important ratio in determining a wire break condition is:

$$A_w / (A_w - A_{def}) \quad (5)$$

Over 100 inclusion and porosity wire breaks were examined and the size of the defect that caused the break was measured; the results of this study are shown in figure 4.25 and in Table 4.6 average wire diameter and defect sizes are listed for different wire break sources.

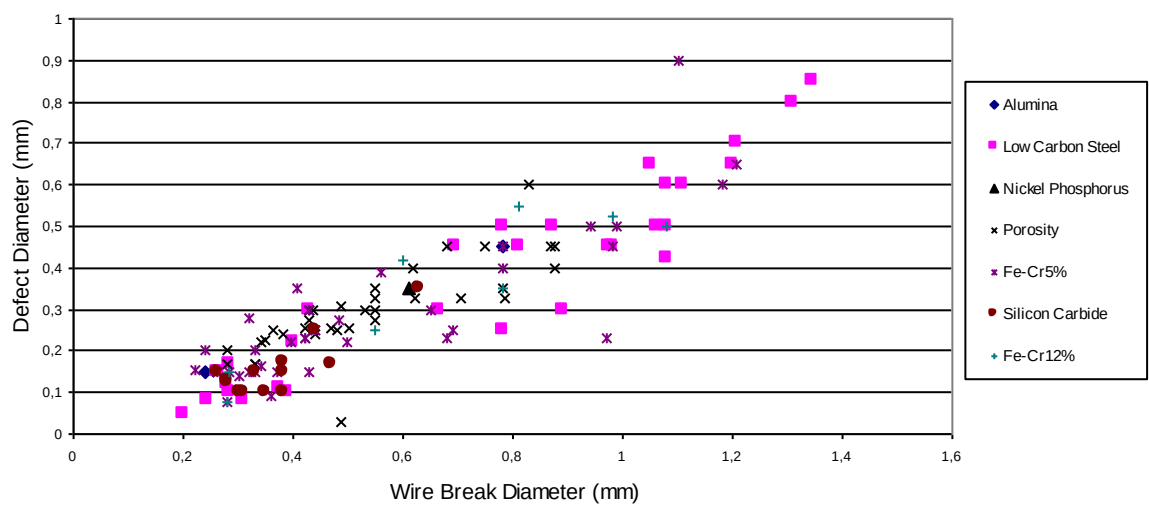


Figure 4.25 Plot of defect diameter vs. diameter of wire at point of break

The wire break diameter of the samples which were investigated, varies between 0.20 mm to 1.40 mm while the defect size varies from 0.03 mm up to 0.90 mm. (Figure 4.25)

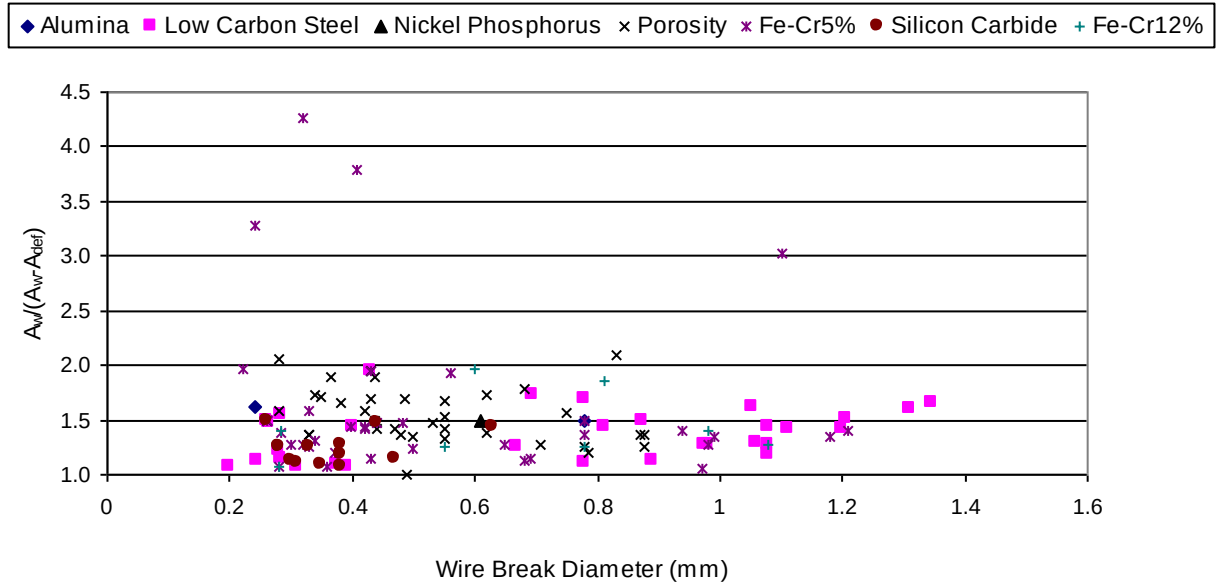


Figure 4.26 Graph showing the relation between $A_w/A_{w-A_{def}}$ values and wire break diameter.

In Figure 4.26, the relation between $A_w/A_{w-A_{def}}$ values and wire break diameters are plotted. It is clear that a poor correlation exists when using the equation of $A_w/A_{w-A_{def}}$ for all defect types. Average wire diameter is about 0.465 mm while average defect size is 0.303 mm. (Table 4.6) As the average wire break diameter decreases, a better wire drawing performance occurs. Porosity has a smaller average wire break diameter compared to the other types of defect except for SiC. SiC has got a very high strength and it is quite brittle compared to copper and will be discussed at a later stage. FeCr5% Steel defect type has a lower average wire break diameter compared to low carbon steel and FeCr12% so this means that it can be drawn to smaller diameters than the other two inclusion types (Low Carbon Steel and FeCr12%) .

Defect Type	Average Wire Diameter (mm)	Average Defect Size (mm)
Low Carb.Steel	0.581	0.373
FeCr5% Steel	0.449	0.288
FeCr12% Steel	0.539	0.353
Silicon Carbide	0.332	0.210
Porosity	0.424	0.291
Average Defect	0.465	0.303

Table 4.6. The effect of defect size on wire break diameter.

Porosity defects will be analyzed in the section on deformable defects(Section 4.1.11.1) while the rest of the defects will be discussed under the topic of non-deformable defects. During the deformation process pores in the wire can deform and change their shapes. In non-deformable defects load transfer takes place across the defect and the bonding of the particle with the matrix is very critical.

4.1.11.1 Drawing Stress Analysis of Copper Wire with Deformable Defects

It is possible to assess the critical value for the ratio of $A_w / (A_w - A_{def})$ if the drawing stress can be estimated. A quick calculation can be made using the simple analytical equation for wire drawing presented in section 2.7.1.

$$\sigma_d = \sigma_y \ln A_0/A_w + (\mu / \tan \alpha) \sigma_y \ln A_0/A_w + 2/3 \sigma_y \alpha \quad (6)$$

In the drawing plant where these breakages occur the reduction per pass is ~17.5% (i.e. Initial Diameter = 1.175 Wire Diameter or $A_0 = (1.175)^2 \cdot A_w$) the die angle is 12° and the friction coefficient can be assumed to be of the order of 0.1. Substituting these values into equation (6) it is found that:

$$\sigma_d = 0.61 \sigma_y \quad (7)$$

Combining equation 7 and 4 the following critical ratio can be calculated:

$$A_w / (A_w - A_{def}) > 1.64 \quad (8)$$

This assumes that the presence of the defect does not contribute to an increase in drawing stress, and this is most appropriate for porosity defects.

Equation (8) will be referred to as Critical Ratio-1 for the rest of the thesis. The calculated Critical Ratio-1 is 1.64 such that for $A_w / (A_w - A_{def})$ above this value wire breaks will occur. As the defect diameter increases $A_w / (A_w - A_{def})$ increases.

The data regarding porosity defects from the experimental work plotted for the ratio $A_w / (A_w - A_{def})$ in Figure 4.27.

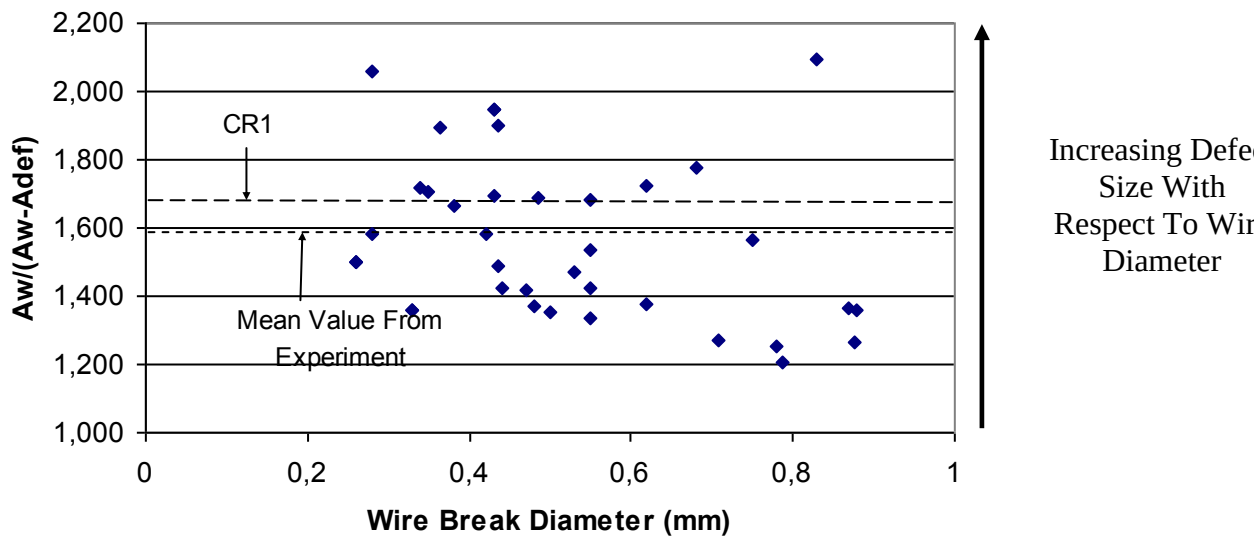


Figure 4.27 Graph showing the relation between $A_w/(A_w - A_{def})$ values and defect size.

From Figure 4.27, it is found that the average Critical Ratio-1 is about 1.56 which is slightly lower than the calculated value. Normally one would expect to obtain a higher value than the calculated ones, because during the calculation of the Critical Ratio-1 work hardening of the wire was ignored. Work hardening of the wire increases the flow stress of the wire on the exit side. This has the effect of making the wire less resistant to failure hence giving a higher value for CR1(Critical Ratio-1).

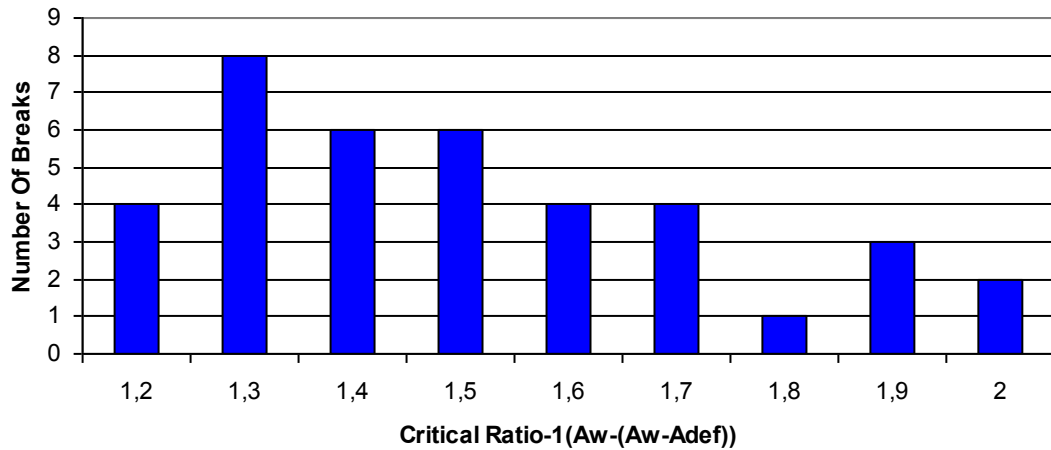


Figure 4.28. The distribution of Critical Ratio-1 values.

In Figure 4.28 the distribution of wire breaks as a function of Critical Ratio-1 is given and it is found that most of the wire breaks are accumulated within the region of Critical Ratios between 1.30-1.60. Theoretically all of the breaks are expected to be observed with a ratio over 1.64. There are three main reasons that can be presented to explain this phenomenon.

1) *Error in Measurement:* During the measurement of pore sizes inside the wire, it is not very easy to make accurate measurements because of the shape of the pores. Looking at a typical pore break (Figure 4.29) it can be seen that estimating the pore diameter is very subjective. M1 and M2 lengths are quite different from each other. In this investigation M1 was chosen as the representative pore size. Significant underestimation of the pore size can occur. It is possible to measure different values for the same pore. The size of the pore is narrower at the end while it reaches its maximum value in the middle. (Figure 4.30) Measurement location can also lead to an underestimation.

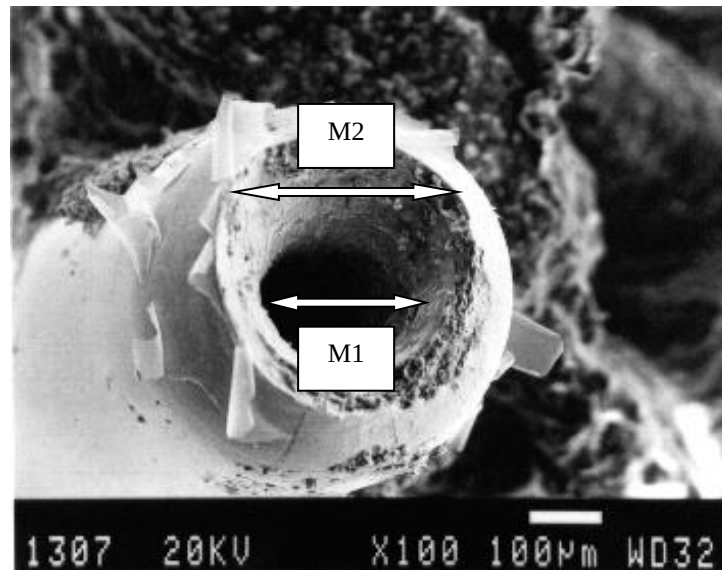


Figure 4.29 Scanning electron microscope photo for a macroporosity break which shows the technique of the measurement of pore sizes.

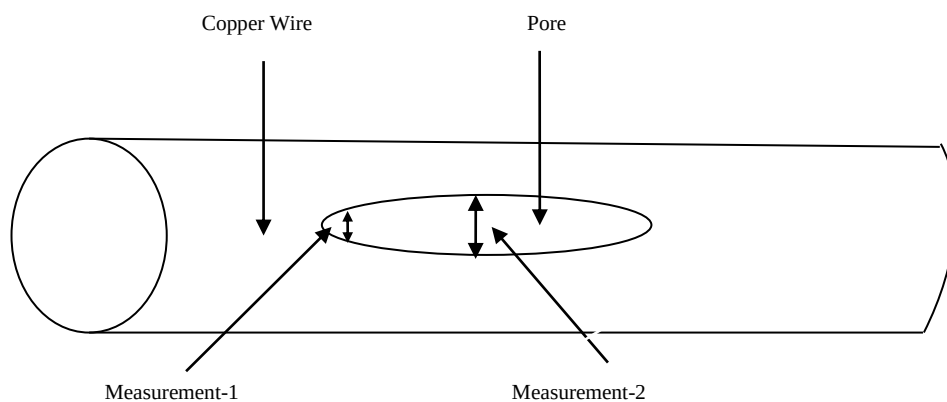


Figure 4.30. Schematic of a porosity defect showing the possible measurement locations.

2) *Location of Pore in Wire:* The position of the pore is also important for the calculation. The pore is assumed to be at the centre in all calculations. If the pore is located close to the wire surface rather than at the centre, failure will occur with pore sizes lower than expected.(Figure 4.31)

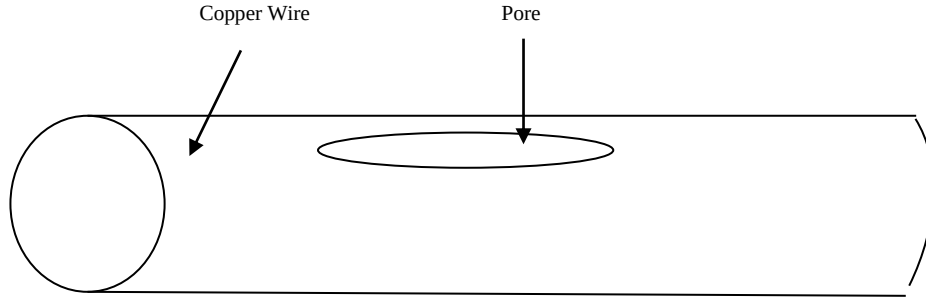


Figure 4.31 Schematic of a pore in copper wire which is located close to wire surface.

3) *Necking of Wire*: Necking can be seen during the wire break occurrence (Figure 4.29). During necking the pore reduces in diameter and hence the measured value is less than that when the neck was initiated. Again this will lead to an underestimation of pore diameter.

4.1.11.2 Drawing Stress Analysis of Copper Wire with Non-Deformable Defects

If the defect is a non deformable particle then the drawing stress will be significantly higher than predicted by Equation-5. This situation is analogous to tube drawing over a moving mandrel which can be estimated using the following equation;

$$\sigma_d = \sigma_y \ln\{(A_o - A_{def})/(A_w - A_{def})\} + (\mu / \tan \alpha) \sigma_y \ln\{(A_o - A_{def})/(A_w - A_{def})\} + 2/3 \sigma_y \alpha \quad (9)$$

If we assume that there is a good adherence between the copper and the particle such that load transfer takes place across the defect then it is possible to calculate the critical defect size to cause a wire break (i.e. the condition when $\sigma_d > \sigma_y$).

$$\ln\{(A_o - A_{def})/(A_w - A_{def})\} + (\mu / \tan \alpha) \ln\{(A_o - A_{def})/(A_w - A_{def})\} + 2/3 \alpha > 1 \quad (10)$$

$$\ln\{(A_o - A_{def})/(A_w - A_{def})\} > 0.585 \quad (11)$$

$$(A_o - A_{def})/(A_w - A_{def}) > 1.8 \quad (12)$$

$$((1.38) \cdot A_w - A_{def})/(A_w - A_{def}) > 1.8 \text{ (Critical Ratio-2)} \quad (13)$$

Equation (13) will be referred to as Critical Ratio-2(CR2) for the rest of the thesis.

Figure 4.32 gives a plot of Critical Ratio-2 as a function of wire break diameter.

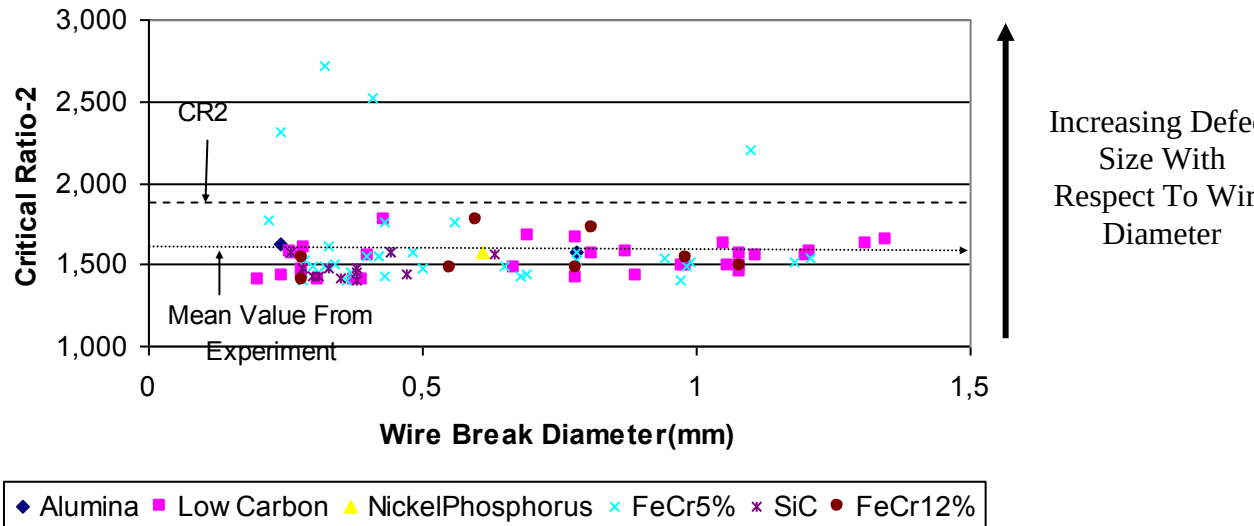


Figure 4.32 Critical Ratio-2 against wire break diameter for inclusion breaks.

A summary for the plotted diagram is given in Table 4.7. Alumina and nickel-phosphorus originated breaks are ignored in the summary because of the insufficient number of data points. The origin of each defect is also provided.

Defect Type	Average Value of Critical Ratio-2	Origin of Defect
FeCr5%	1,63	Hot Rolling
FeCr12%	1,55	Cold Rolling
Low Carb.Steel	1,53	Wire Drawing
SiC	1,48	Casting
Average	1,57	

Table 4.7. Overview of inclusion related breaks.

As can be seen from Figure 4.32, with the exception of some of the FeCr5% breaks, an excellent correlation is obtained with the majority of wire breaks having a Critical Ratio-2 of ~ 1.4 – 1.6.

All the average CR2 values for different defect types are lower than the calculated value of 1.8 (Table 4.7). FeCr5% has got the highest value of CR2 of all the defect types. FeCr5% defects originate in the hot-rolling process which takes place at a temperature of about 860°C. This high working temperature and the rolling deformation produce good bonding between the inclusion-FeCr5% and the copper matrix. This good bonding leads to load transfer across the defect and thus a higher CR2 value can be achieved.

FeCr12% and low carbon steel defects originate during the cold rolling and drawing processes. Their CR2 values are not as good as that of FeCr5% defects. Although low carbon steel and FeCr12% defects originate in the deformation processes similar to FeCr5% defects, the low temperature prevent good bonding from occurring. (The working temperature is around room temperature although localized heating occurs during the deformation.) It should be noted that it is possible to have these type of inclusions very close to the wire surface.

SiC has got the lowest CR2 value of all defect types. During the casting operation some reaction is likely to occur between the SiC particles and the copper matrix. This will result in an interfacial reaction product. During the wire drawing process the brittle reaction product fractures leading to poor load transfer. On further deformation the SiC particles, which are extremely strong but brittle, also fracture. This means that when wire breakage occurs it is difficult to determine the defect size.

Empirically it can be concluded that 1.5 is the critical value for CR-2 for the occurrence of the wire breaks and equation (13) can be modified as follows;

$$((1.38).A_w - A_{def}) / (A_w - A_{def}) > 1.5 \quad (14)$$

For a failure occurrence

$$d_w < 2.04 d_{def} \quad (15)$$

This means that when the defect size reaches approximately half of the drawn wire diameter, a wire break occurs.

The final critical analysis that can be performed is as above, however with the condition that there is poor adherence between the copper and the defect such that no load transfer occurs across the defect. (i.e the condition when $\sigma_d A_w / (A_w - A_{def}) > \sigma_y$)

$$\sigma_d = \sigma_y \ln\left\{\frac{(1.38) \cdot A_w - A_{def}}{A_w - A_{def}}\right\} + (0.47)\sigma_y \ln\left\{\frac{(1.38) \cdot A_w - A_{def}}{A_w - A_{def}}\right\} + (0.14)\sigma_y \quad (16)$$

$$(1.47) \ln\left\{\frac{(1.38) \cdot A_w - A_{def}}{A_w - A_{def}}\right\} + (0.14) > (A_w - A_{def}) / A_w \quad (17)$$

$$(1.47) \ln\left\{\frac{(1.38) \cdot A_w - A_{def}}{A_w - A_{def}}\right\} - (A_w - A_{def}) / A_w > (-0.14) \quad \text{(Critical Ratio-3)} \quad (18)$$

Equation (18) will be referred to as Critical Ratio-3(CR3) for the rest of the thesis.

The wire break diameter for inclusion breaks versus Critical Ratio-3 is plotted in Figure 4.31 and a poor correlation is obvious.

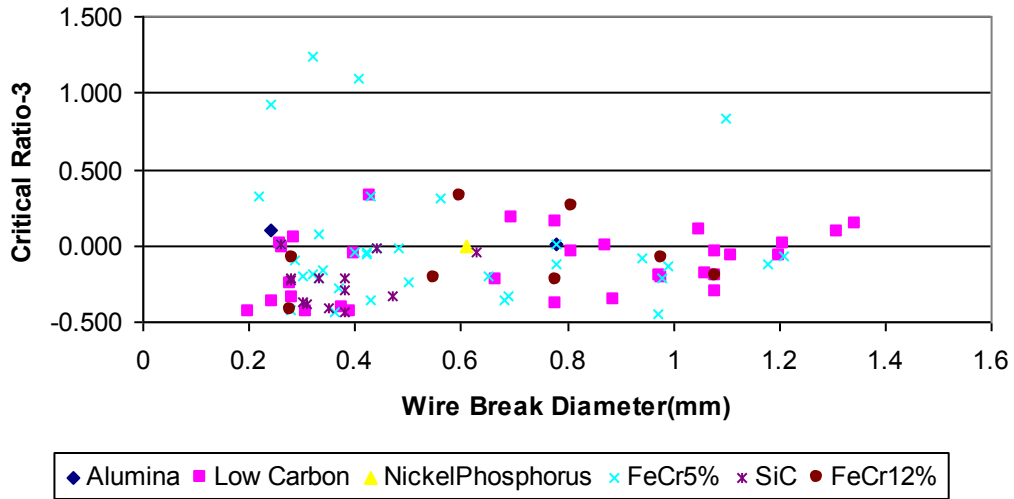


Figure 4.31. Wire break diameter against Critical Ratio-3.

4.2 Experimental Modelling Validation

The previous section (Section 4.1) contained a detailed account of the break types in the copper wire drawing process. There follows an analysis of the drawing stress associated with each type of break. It was found that inclusion and macroporosity breaks were the crucial break types.

Experimentally it is not easy to introduce controlled sized defects and controlled distributions of the defects during the production of copper wire so it was thought that a model would provide a good means of investigating these parameters in a more controlled way. Before using the model to predict wire drawing behaviour it was necessary to perform some wire drawing experiments in order to validate the model.

The data obtained from the wire drawing experiments, the compression test results of the extruded input material and data which was extracted from literature about copper were all used as the input data for the validation of the commercial metal forming software model Forge2.

After the validation of the model a more detailed study of inclusion and macroporosity breaks was carried out.

4.2.1. Experimental Wire Drawing Loads

Table 4.6. shows the values of the drawing loads for the duplicate experiments that were carried out. These values were then averaged to give a mean drawing load for each reduction.

Reduction	Drawing Load(kN)	Drawing Load(kN)	Average Drawing Load	$\ln A_1/A_2$
(mm)	Experiment-1	Experiment-2		
7.76 to 7.13	3.89	3.86	3.87	0.169
7.13 to 6.35	5.76	5.90	5.83	0.232
6.35 to 5.79	4.03	3.76	3.89	0.185
5.79 to 5.28	3.46	3.54	3.50	0.184
5.28 to 4.76	3.46	3.56	3.51	0.207
4.76 to 4.24	3.31	3.06	3.18	0.231
4.24 to 3.70	Broken	Broken	Broken	0.273

Table 4.6 The drawing loads for the duplicate wire drawing experiments.

The drawing loads for the repeat experiments were very similar. The cross-sectional area of the wire decreases significantly with increasing number of passes and therefore the required load decreases even through the material work hardens.

The wire drawing was interrupted because of the occurrence of a wire break during the reduction from 4.24 to 3.70 mm. This signifies that there was something wrong in the process. For this reason samples were taken at the break, and investigated using a SEM. It was found that a tension break had occurred indicating that the wire drawing conditions were not appropriate for continuation of the process. Die geometry i.e. too small a reduction angle or too long a bearing length or poor lubrication could be the reason for this wire break.

4.2.2. Comparison of the Experimental and Forge2 Predicted Drawing Loads

FEM Modelling of copper wire drawing was carried out using the Forge2 Simulation Package.

The conditions used for the wire drawing experiments were also used for the validation of the model. These are shown below:

Alpha	= 11°
Bearing Length	= 30 % of Wire Diameter
Reduction	= From 7.76 mm down to 3.70 mm
Friction(m)	= 0.1

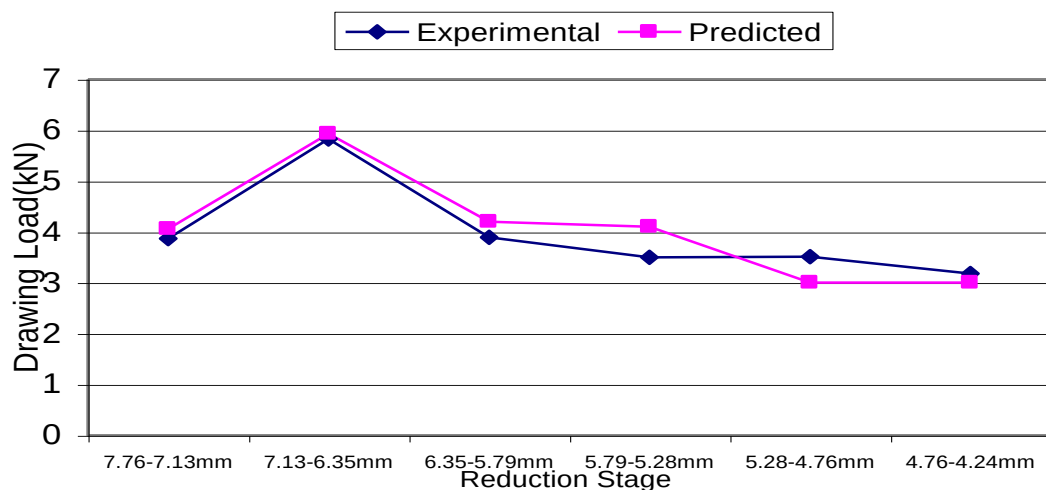


Figure 4.27 The comparison of the experimental and predicted drawing loads.

The experimental values for the drawing loads agreed very well with those predicted by using Forge2, as can be seen in Figure 4.27, hence validating the model.

4.3. Modelling Application

After the successful validation of the Forge2 Model it was then possible to model the behaviour of copper wire containing different types of defect. The standard conditions were ;

Alpha	= 12°
Bearing Length	= 50 % of Wire Diameter
Reduction in Area	= 27.75%
Initial Diameter of Wire	= 10 units
Friction(m)	= 0.1

Four different starting materials were modelled. These were; copper wire without any defect, copper wire containing an undeformable inclusion, copper wire containing a deformable inclusion and copper wire containing a pore.

4.3.1 Defect Free Wire(Sensitivity Analysis)

The effect of variation in the process parameters on the drawing load was analysed within the ranges as follows;

Alpha	= (From 12° to 21°)
Bearing Length	= (From 50 % to 100% of Wire Diameter)
Reduction in Area	= (From 27.75% to 18.46%)
Friction(m)	= (0.1 to 0.4)

In Figure 4.27 variation in variable against variation in load is given. Of the four parameters examined the variation in reduction in area affects the load more than the other parameters even with small changes. Increasing alpha leads to a significant decrease in drawing load over the range studied. Bearing length has little or no effect. All three of these variables are accurately known and will not vary under normal operating conditions. The most critical parameter is friction. Friction conditions are difficult to estimate and can vary during practical wire drawing operations due to lubrication breakdown, etc. As can be seen increasing friction leads to a significant increase in drawing load.

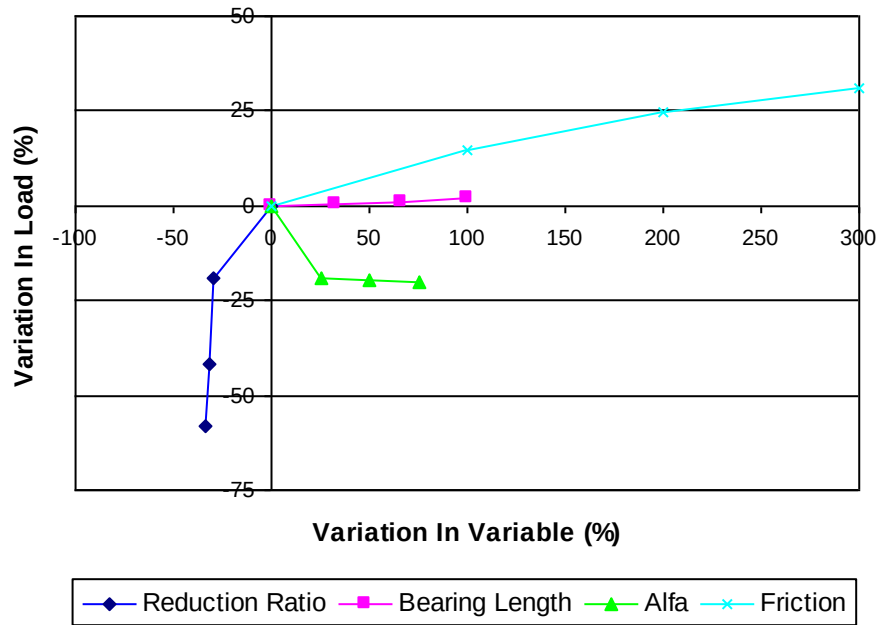


Figure 4.27. Effect of variation of process parameters on the drawing load for defect free wire.

4.3.2 Undeformable Inclusion Wire(Sensitivity Analysis)

The effect of variations in the process parameters on the drawing load was analysed for a 3 mm diameter inclusion within the process ranges as follows;

Alpha	= (From 12° to 15°)
Bearing Length	= (From 50 % to 66,7% of Wire Diameter)
Reduction in Area Ratio	= (From 27.75% to 18.46%)
Friction(m)	= (0.1 to 0.2)

In Figure 4.28 variation in variables against variation in load is given for a wire containing an undeformable defect. The behaviour of the parameter against variation in drawing load is practically the same as in defect free wire. The trends are similar, however the magnitude of the variations are lower indicating that the presence of the inclusion dominates the drawing load. Obviously, the presence of an undeformable inclusion increases the drawing load.

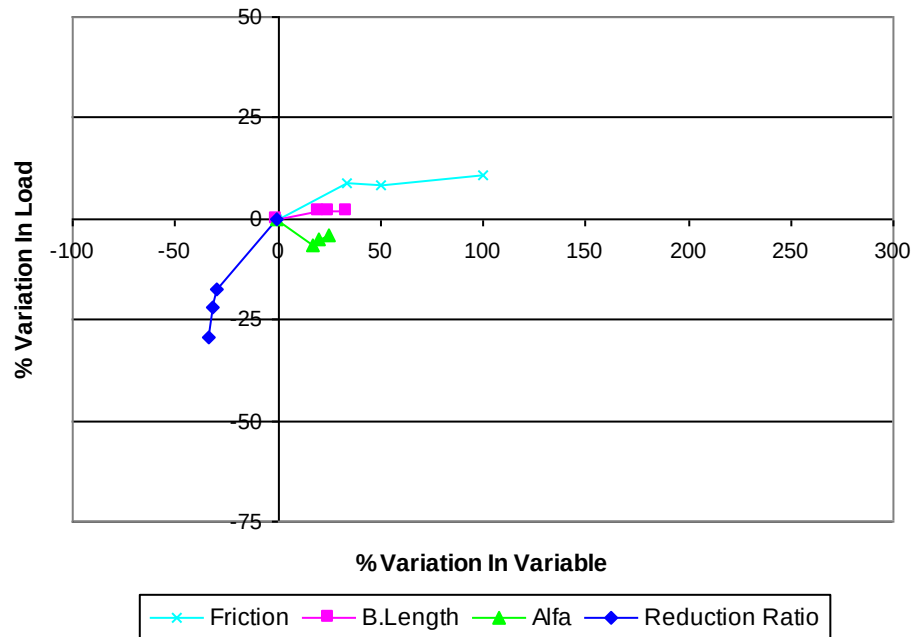


Figure 4.28. Effect of variation of process parameters on the drawing load in wire containing an undeformable defect.

4.3.3 Undeformable Inclusion(Break Prediction)

Copper wire containing an undeformable inclusion was modelled for inclusion sizes varying from 1 unit to 6 units. (Original wire diameter is 10 units.)

For comparison purposes a defect free wire was also modelled. For the defect free wire the surface of the wire experienced a higher strain(0.4) than the centre(0.3) because of the friction between the wire and the die (See Figure 4.29-a).

When a small undeformable inclusion (3 units) is incorporated into the wire (See Figure 4.29-b), the strain distribution changes. The inclusion acts as a stress concentrator resulting in increased strain intensity (0.5) above and below the inclusion.

For a larger inclusion (6 units) the strain intensity increases in the vicinity of the inclusion to values of 0.7-0.9 (See Figure 4.29-c). There is also clear evidence of necking in the wire at the exit which indicates that failure will result.

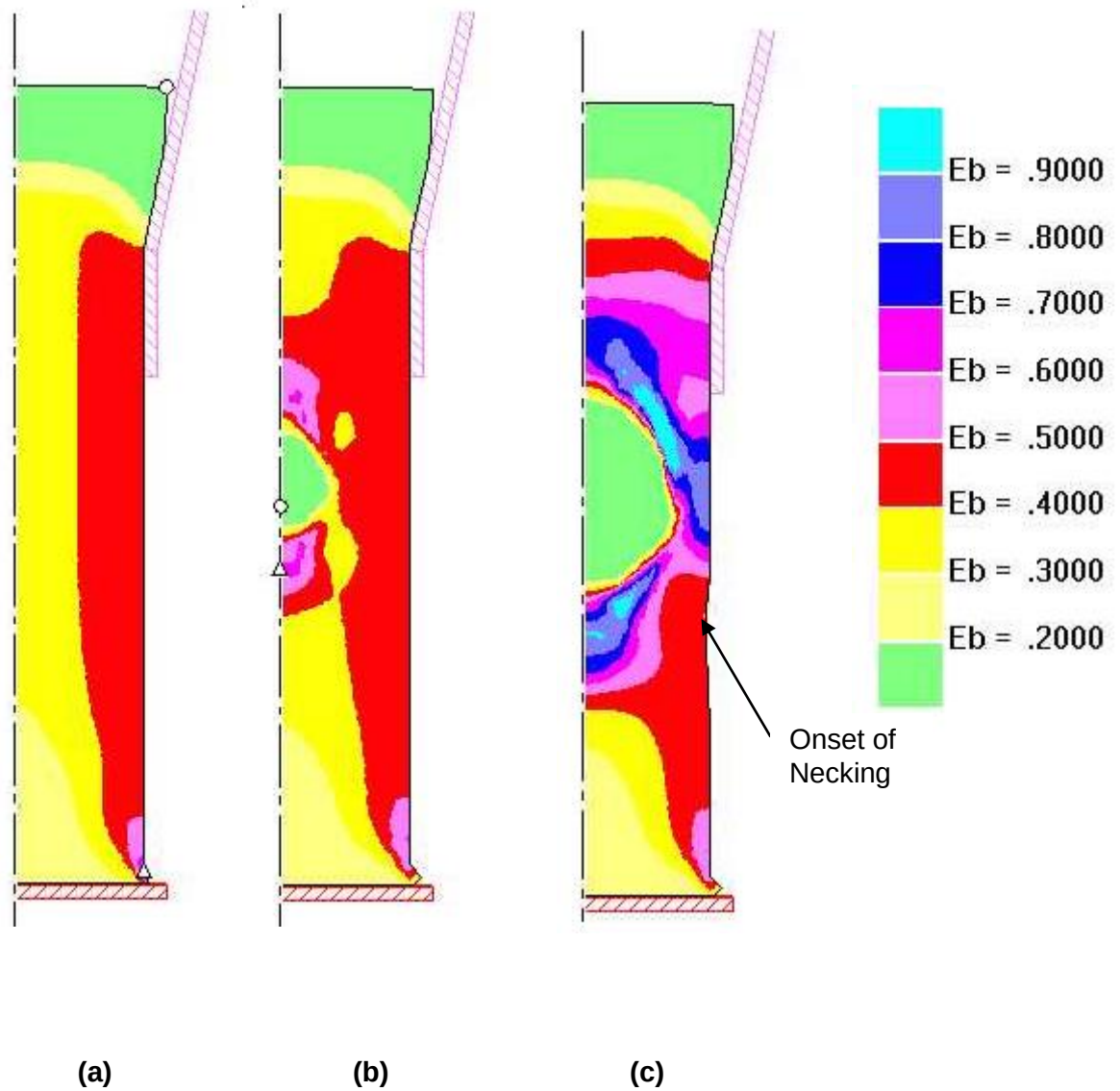


Figure 4.29. Strain distribution (true strain) in defect free wire (a) and wire containing an inclusion of 3 units (b) and 6 units. (c)

As can be seen in Figure 4.30, as the inclusion size increases the wire drawing load increases significantly.

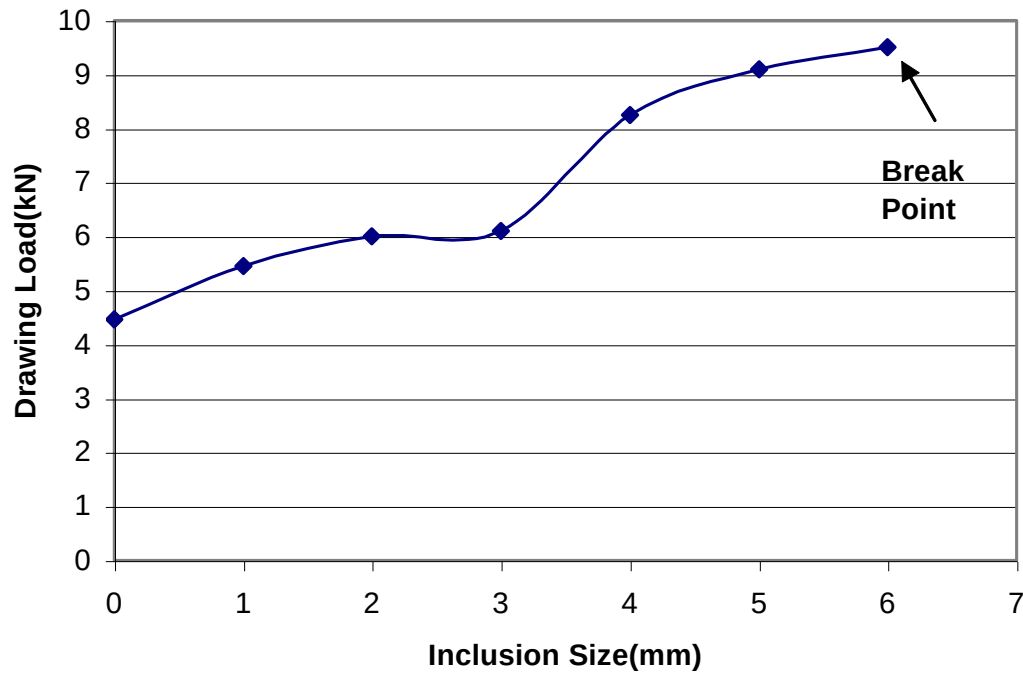


Figure 4.30. The effect of inclusion size on drawing load.

CR-2 value which was used for the prediction of the wire break incidence in wire containing an undeformable inclusion was found in Section 4.1.11 as 1.8, but it was modified experimentally to 1.5. In the modeling, wire containing an inclusion size of 6 units resulted in a wire break occurrence and the CR2 value was determined as 1.59. This shows excellent agreement between the experimental and predicted values.

4.3.4. Deformable Inclusion Gap(Break Prediction)

In the previous section 4.3.3 it was shown that an undeformable inclusion of 6 units in diameter caused a wire break. It is believed that if the inclusion is deformable, however, it will require an inclusion greater than 6 units in diameter to cause failure. In order to demonstrate this three runs were carried out using the model. The conditions for the three runs were:

- (a) Undeformable inclusion (7 units) in annealed copper,
- (b) Deformable inclusion (7 units) in annealed copper,
- (c) Deformable inclusion (7 units) in hard drawn copper.

The flow stress data for the deformable inclusion and for the annealed and hard drawn copper are shown in Figure 4.31. The inclusion type chosen was mild steel and clearly it has a much higher flow stress than ever the hard drawn copper.

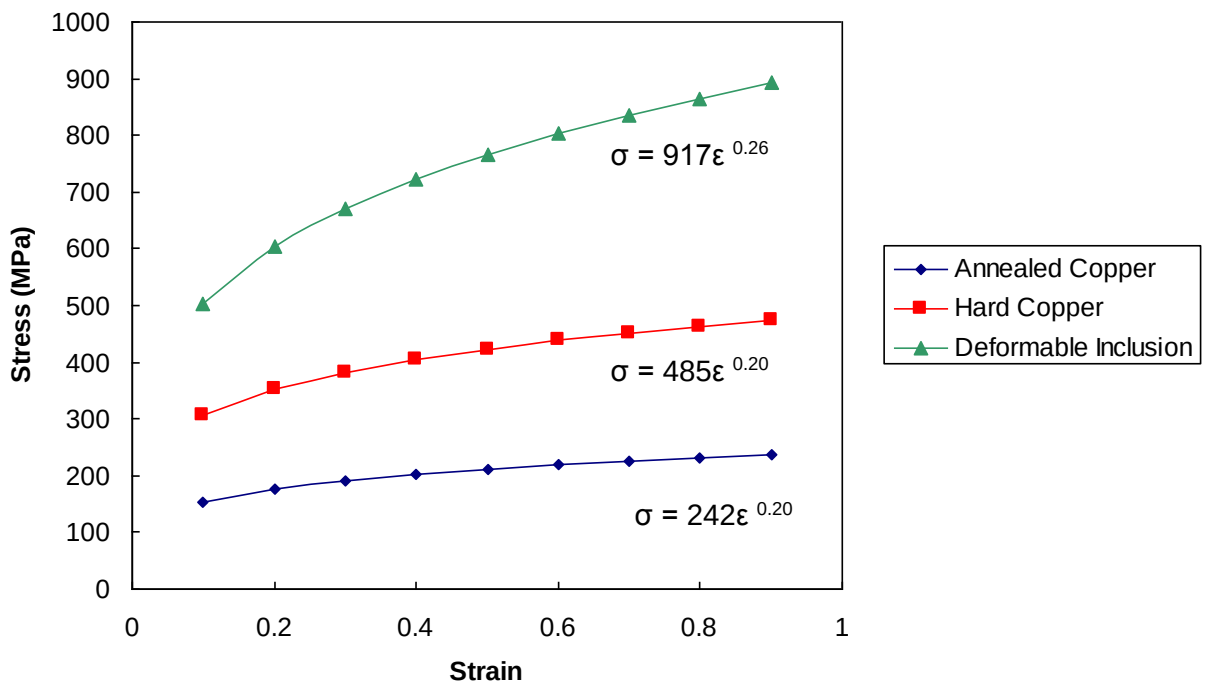


Figure 4.31 Flow stress of annealed copper, hard copper and deformable inclusion. [46]

Figure 4.32-a) shows the strain distribution for the undeformable inclusion in annealed copper wire. This mirrors the behaviour shown in Figure 4.29-c) for an undeformable inclusion of 6 units in diameter. The inclusion acts as a stress concentrator resulting in increased strain(0.8) in the copper below the inclusion and clear evidence of necking is shown. Figure 4.32-b) shows the case of the deformable inclusion in annealed copper. This time the strain in the copper in the vicinity of the inclusion is reduced(0.6) because some of the deformation was accommodated by the inclusion. There is still a slight indication of necking which shows that fracture will occur.

Finally, in Figure 4.32-c we see the strain distribution for the case of the deformable inclusion in hard drawn copper. The strain in the copper in the vicinity of the dislocation has been reduced significantly(0.4) because the stronger matrix has resulted in even more deformation being accommodated by the inclusion. This time there is no evidence of necking indicating that under these conditions the wire can be successfully drawn. Thus we have shown that the maximum size of inclusion which can be tolerated in the wire drawing process i.e. without causing a wire break, is larger if the inclusion is deformable.

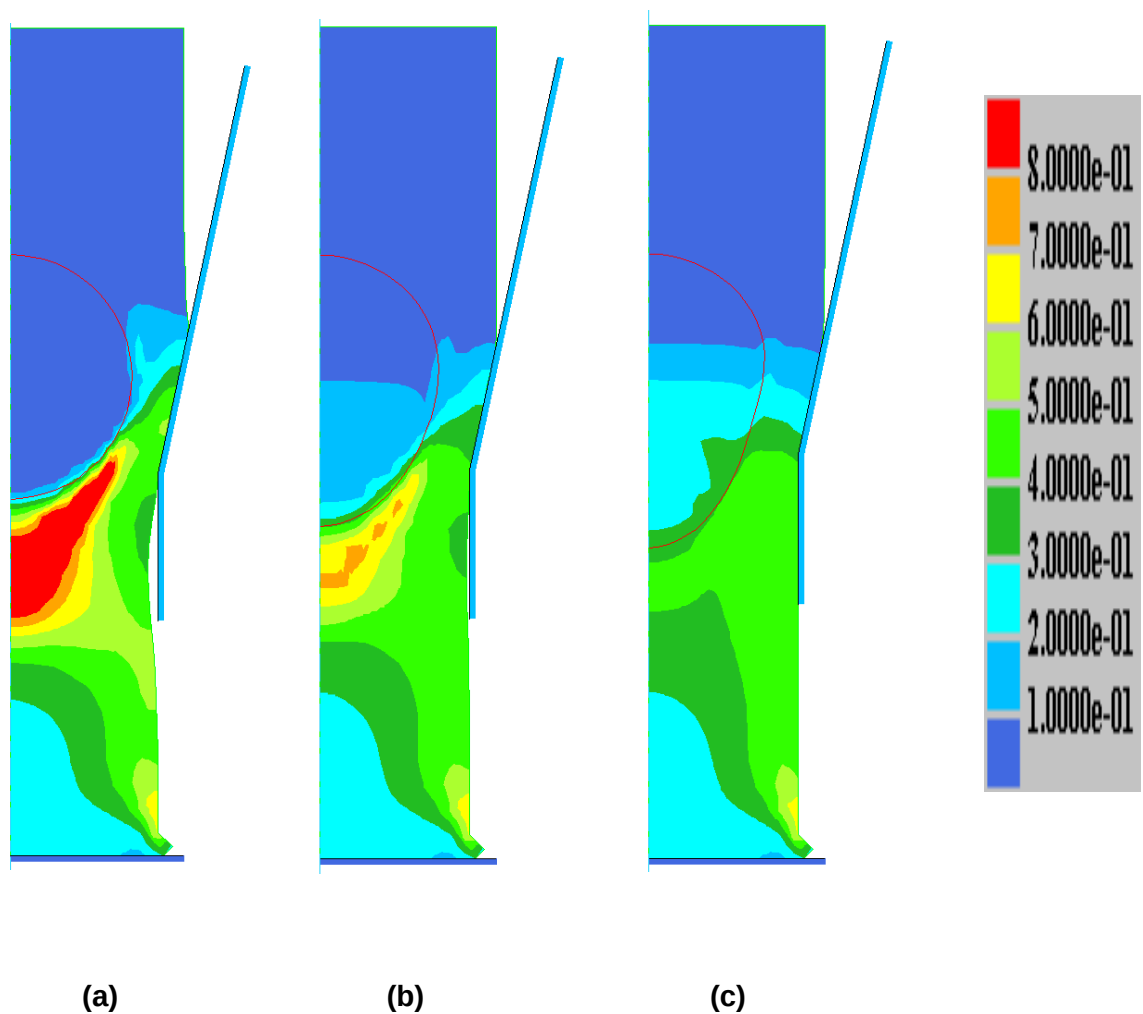


Figure 4.32. Strain distribution of an inclusion(7 units diameter) a)undeformable in annealed copper, b) deformable in annealed copper, c) deformable in hard drawn copper.

4.3.5. Porosity(Break Prediction)

Copper wire containing porosity was modelled for pore sizes varying from 1 unit to 7 units. A small pore (4 units) does not affect the situation much except to produce a

more concentrated strain area (0.4) in the region of the matrix-pore interface (See Figure 4.33-b.) For a larger pore (7 units) the strain in this region is reduced (0.3) compared to that for the smaller pore (Figure 4.33-c), because more of the deformation was accommodated by the larger pore. The onset of necking in this region is also clearly shown which indicates that failure will result necking in this region is logical as the relatively low strain means that little work hardening would have occurred here and thus the matrix is weak.

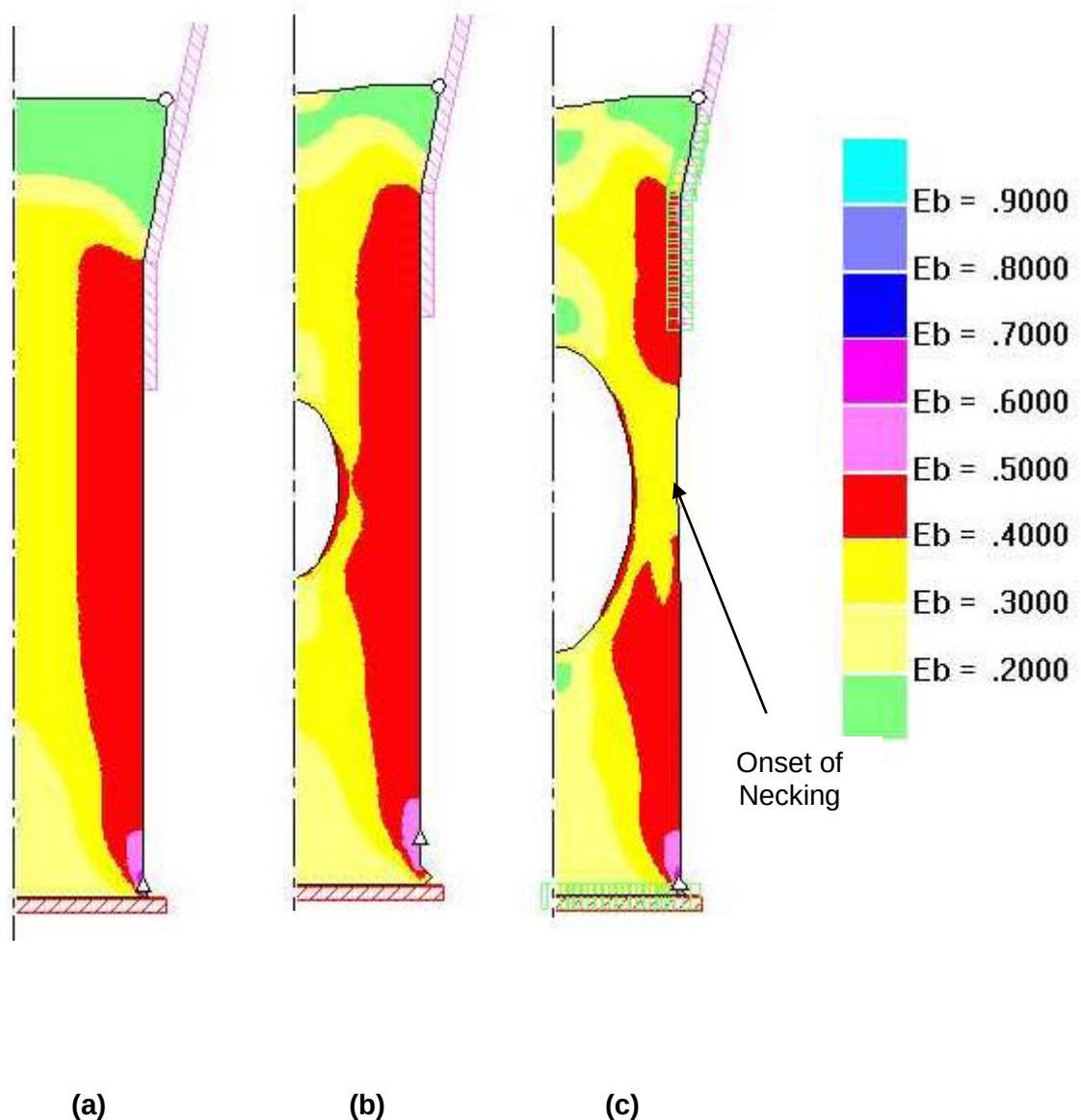


Figure 4.31. Strain distribution(true strain) in defect free wire (a) and wire containing a pore of 4 units (b) and 7 units. (c) (Wire diameter is 10 units)

When there is a pore in the wire, the drawing load required is generally less than the drawing load for defect free wire.

According to Critical Ratio-1 as previously mentioned in Section 4.1.11, a calculated value of 1.64 was found. In the model wire containing a pore size of 7 units a wire break resulted and the Critical Ratio-1 value was determined as 1.96. It was stated in Section 4.1.11 that for a Critical Ratio-1 value above 1.64, a wire break is likely to happen. In this case, the model wire containing a pore confirmed the calculated Critical Ratio-1 value.

CHAPTER 5

CONCLUSIONS

In total, 4260 industrial wire break samples were examined in this project and a detailed classification of the types of breaks developed. Almost half of these wire breaks were determined as “Inclusion” and “Macroporosity” types and these breaks were investigated in detail, because fine and superfine multiwire diameters are particularly susceptible to these kinds of breaks. The rest of the wire break types such as V Shape Defect, Tension Break, Split End, W.D.P., and Central Burst breaks generally occurred because of improper wire drawing practices.

Inclusion and macroporosity breaks generally occurred because of improper process conditions during the wire drawing process. It was found that improper SCR and wire drawing process conditions were predominantly responsible for inclusion breaks: wire drawn from Outokumpu copper was found to be less susceptible to non drawn-in inclusion breaks.

There was no discernable difference in the incidence of macroporosity breaks in copper produced from the two casting routes SCR and Outokumpu. The reason for the higher number of inclusion breaks observed in the SCR copper rod can simply be explained in terms of the production method. In SCR the copper is cast and rolled to yield the feedstock for the drawing process, whilst Outokumpu copper feedstock is supplied in the as cast condition. In the latter process only refractory type inclusions are found, whilst in SCR copper inclusions derived from the rolling mills are also present.

Low carbon steel, FeCr5%, SiC, FeCr12%, Al₂O₃ and nickel-phosphorus were determined as the inclusion sources in this study. It was found that the majority of the breaks were related to ferrous based inclusions. 50% of inclusion breaks occurred in wire under 0.35 mm diameter.

As a result of this investigation several improvements have been made to the production methodology employed at the sponsoring company's plant. These include, the introduction of ceramic coated steel guide rolls, more frequent roll changeover on the SCR line, and the introduction of a modified up-cast Outokumpu

line directly casting to 8-mm diameter. The combined effect of these improvements has been to increase the average drawability on the multiwire lines from ~ 1000-kg per break to over 5000-kg per break.

It has been shown that several process improvements can be made to severely reduce the occurrence of wire breaks. However it is not feasible to eliminate inclusions altogether, and periodically wire breaks will occur.

The critical ratio ($A_w / (A_w - A_{def})$) can be used to help us understand the effect of defect size on the performance during wire drawing. Over 100 inclusion and porosity wire breaks originating from industry were examined and the size of the defect that caused the break was measured. A poor correlation was observed when using the equation of $A_w / (A_w - A_{def})$ for all defect types taken together.

The critical ratio is assessed by inserting values for the wire drawing process parameters in the equation for drawing stress (Equation-6) and is calculated as $A_w / (A_w - A_{def}) > 1.64$ (Critical Ratio-1 or CR1). The calculated CR1 is 1.64 such that for $A_w / (A_w - A_{def})$ above this value wire breaks will occur. As the defect diameter increases $A_w / (A_w - A_{def})$ increases. For industrial samples it was found that the average CR1 is about 1.56 which is slightly lower than the calculated value. Normally one would expect to obtain a higher value than the calculated one, because during the calculation of the CR1 work hardening of the wire was ignored. Work hardening of the wire increases the flow stress of the wire on the exit side. This has the effect of making the wire more resistant to failure hence giving a higher value for CR1. Theoretically all of the breaks are expected to be observed for ratios greater than 1.64. Errors in pore size measurement, location of pore in wire and necking are the three main reasons that can be presented to explain this phenomenon.

For a non deformable particle with good adherence between the copper and the particle the equation of $((1.38) \cdot A_w - A_{def}) / (A_w - A_{def}) > 1.8$ (Critical Ratio-2; CR2) was developed. An excellent correlation was obtained with the majority of wire breaks having a CR2 of ~ 1.4-1.6. All of the average CR2 values for different defect types were lower than the calculated value of 1.8. FeCr5% had a higher ratio compared to other defects. Experimentally the CR2 equation was modified to $((1.38) \cdot A_w - A_{def}) / (A_w - A_{def}) > 1.5$, and finally for a failure occurrence $d_w < 2.04 d_{def}$ was developed which

means that wire break occurred when the defect diameter reached approximately half that of the drawn wire.

A poor correlation between wire break diameter and Critical ratio-3 was achieved for the condition of poor adherence between the copper and the defect.

The experimental values for the drawing loads for each reduction stage matched very well with those predicted using Forge2. Drawing loads in each reduction stage varied between 3-6 kN.

The drawing behaviour of five different starting materials was modelled. These were: annealed copper wire without any defect, annealed copper wire containing an undeformable inclusion, annealed copper wire containing a deformable inclusion, hard drawn copper wire containing a deformable inclusion and copper wire containing a pore. The effects of variations in several process parameters on drawing load were investigated. The parameters chosen were reduction angle, die bearing length, friction factor and reduction in area. All process parameter variation trends against drawing load were similar for the different types of materials, but the magnitude of the variation was lower in the case of inclusions (both deformable and undeformable inclusions).

From the wire drawing model wire containing an inclusion of 6 units in size experienced a wire break and the CR2 value was determined as 1.59. Wire containing a pore size of 7 units also experienced a break and the CR1 value was determined as 1.96. In both cases good agreement between the experimental and predicted values were achieved.

It was shown that the maximum size of inclusion which can be tolerated without causing a wire break increased if the inclusion was deformable.

The CR2 value can be used in order to classify the wire quality during wire drawing. By the help of the Ferromat dedector, the size and number of magnetic inclusions can be determined during the continuous casting rod and wire drawing processes. These data can be used to calculate the CR2 values and finally classification of the wire quality can be made.

CHAPTER 6**SUGGESTIONS FOR FURTHER WORK**

In this project wire breaks from two major types of materials (Southwire and Outokumpu) were investigated. This study can be enlarged by observing the other types of continuous casting systems such as Contirod and Properzi and a broad classification can be made.

Variation of the classification of wire breaks over a trial period for a constant final product can be compared to the variation of drawability values in wire drawing plants. (i.e. 3 months of trial period, 0.10 mm final product diameter, and drawability values can be determined from the number of wire break occurrences and production quantity. It would be useful to find what type of wire breaks are significant in different types of feedstock material. This would enable the selection of material for wire drawers to be made more carefully so that efficiency and quality increase.

An alternative to prevention of inclusion breaks is detection. Several methods (e.g. Ferromat Dedection) are already used industrially to detect inclusions prior to wire drawing. However these methods do have their limitations. There is a trade off between inclusion size and section thickness within which the inclusion can be detected. To detect a small inclusion, only a thin section of rod (the surface layer) can be screened. This type of screening is limited to detecting larger surface inclusions, and smaller central inclusions are not generally detected. What would be useful is a knowledge of critical inclusion size for a particular final wire diameter (i.e. The maximum defect size allowable for a break free wire). Once known it would be possible to place detection systems at strategic locations throughout the drawing plant, each detector set at a frequency to detect these inclusions. In the larger wire diameters, the finer inclusions would not hinder the wire drawing process and therefore the detection systems could be set at low frequencies to detect the larger critical inclusions through the whole section of the wire. As the wire is drawn down, the frequency of the detection systems can be increased to detect finer inclusions; as the section thickness is reduced, detection across the whole wire diameter is possible.

In this Project, inclusion breaks in detail were investigated deeply which were originated in industry. Various type of inclusions can be added into the copper wire

rod during the casting process. The type, amount and size of the inclusions can be controlled during casting process. Afterwards by the help of extrusion process copper wire rod with a diameter of-8mm can be achieved and for the following process wire drawing can be done until a wire break occurrence can be seen. Magnetic steel, non-magnetic steel, iron and refractory inclusions can be added starting with a size of 0.5 mm up to 5-6 mm. The drawability, microstructure, physical and electrical properties of the wire can be observed. At the same time a modelling process for similar conditions can be operated and comparisons and more detailed studies can be made especially on microstructure, drawability, physical and electrical properties of the wire.

REFERENCES

- (1) "Extractive Metallurgy of Copper", A.K.Biswas, W.G.Davenport, Pergamon Press, 1976, Great Britain.
- (2) "Hot Working of Copper and Copper Alloys", Frank F.Poland, Copper, A.Butts, American Chemical Society, 1954, New York.
- (3) "Copper Rod Production", Published by International Wire and Machinery Association, England, 1995.
- (4) "Cathode Melting and Casting of Marketed Copper Shapes", R.H.Waddington, Copper, 1954, New York.
- (5) "Copper Wire and Cable", Metals Handbook, Volume 2-Properties and Selection Nonferrous Alloys and Pure Metals, 1979, USA.
- (6) "Technical Advances in the new SCR Copper Rod Mill", E.H. Chia, Nonferrous / Electrical Divisional Meeting of the WAI, 1983, Texas.
- (7) "Upcast – The Process, Equipment and Know How of Making High Quality Copper Wire Rod For Cable and Enamelled Wire Industry", S.Pietila, International Congress Aachen, IWMA, 1991.
- (8) "Fundamental Comparison of the Mechanical Behaviour of Oxygen Free and Tough Pitch Coppers", W. R. Opie, P.W. Tavbenblat, and Y.T. Hsv, Journal of the Institute of Metals, 1970.
- (9) "CRV Copper Studies", Volume 20. No: 11, CRV International Ltd. May 1993, London.
- (10) "Competition To SCR", SCR User Meeting, 1996, Georgia.
- (11) "The Metallurgie Hoboken-Overpelt Process for the Continuous Casting and Rolling of Copper Rod Wire Production, Contirod", J.A.De Keyser, SCR User Meeting, 1985, Georgia.

- (12) "Competition To SCR Systems", M. Berry, SCR User Meeting, 1993, Georgia.
- (13) "Nonferrous Wire Handbook" Volume 3-Principals and Practice, Published by The Wire Association International, Inc. Guildford, Connecticut, USA, 1995.
- (14) "The SCR Continuous Copper System From Melt To Wire", E.H. Chia, R.D. Adams Southwire Company, 1980.
- (15) "The Metallurgy of Southwire Continuous Rod", E.H. Chia, R.D. Adams, Journal of Metals, Feb. 1981.
- (16) "Southwire Continuous Rod Proces Innovations for Quality Improvements", V. Sinha, R. Adams, Wire Journal Int, June 1993.
- (17) "Improving the Quality of Continuous Copper Rod", R. Adams, V. Sinha, Journal of Metals, May 1990
- (18) "Southwire Continuous Rod (SCR) Meeting Today`s Demand and Tomorrow`s Rquirements For Copper Quality", R.D.Adams, D.B. Cofer, V. Sinha, SCR User Meeting, 1988, Georgia.
- (19) "Continuous Casting and Rolling of Copper Rod", J.A.Bell, D.B.Cofer, Wire and Wire Product, 1967, New York.
- 20) "The Merit, of Small SCR Systems", Yea – Yang Su, SCR User Meeting, 1985, Georgia.
- (21) "Enamelling Wire of Tough Pitch Copper Produced by SCR System", K.Nakano, M.Shibata, SCR User Meeting, 1988, Georgia.
- (22) "The Role of Nickel and Zinc in ETP Copper", H. Pops, J. Hollaman, Wire J. Int, Feb.1996.
- (23) "Reduction of Impurities in Copper", T. Zaheen, Wire Industry, Oct. 1995
- (24) "Impurity Effects in High – Conductivity Copper", Y.T. Hsvand B. O`Reilly, J. Metals, Dec. 1977.

- (25) "Effects, of Impurities on the Annealability and Resistivity of Oxygen – Bearing Copper", Bigelow, J.H. Chen, Metallurgical Transactions B, Volume 7 B, Dec.1976
- (26) "The Influence of Oxygen During Hot Rolling and Drawing of Continuous – Cast Rod", J. Smets, R. Mortier, Wire J.Int. Nov. 1984.
- (27) "Characterization of Rod and Wire Defects Produced During the Manufacturing of Copper", E.H. Chia, G.R. Patel, Wire Journal Int., June 1996.
- (28) "Organic Additives and Hydrogen in Copper Cathodes", E.H. Chia, Y.Y., Journal of Metal, April, 1987.
- (29) "Gas and Other Impurity Reaction in Copper", A.J. Phillies, Metallurgy Transactions, Volume-4, August, 1973.
- (30) "The Effects of Impurities on the Recrystallization Behaviour of ToughPitch Hot Rolled Copper Rod", R. Feyaerts, P. Haybrechts, J. Schang, J.Van. Hunberck, B. Verlinden Wire J.Int. Nov.
- (31) "The Effect of Impurities in Copper", J.S. Smart, Copper- A. Butts, American Chemical Society, 1954, New York.
- (32) "C.C.I. Rod Classification Tests", G. Baldassarri, SCR User Meeting October 1978 Atlanta, USA.
- (33) "Copper Rod Requirement for Magnet Wire", H. Pops, Wire J. Int. May.90
- (34) "Torsional Stress Test for Copper Rod, Indicator of Quality and Performance", E.H.Chia, D. Adams,SCR User Meeting, 1986, Atlanta.
- (35) "On the Origin of Twist Test Cracks in Copper Rod", H. Pops G. Lingsb, Wire J. Int,Jan. 1988.
- (36) "A New Concept in the Evaluation of the 10x10 Twist Test for Copper Rod", R.L.Hamill, S.K.Young, Wire J.Int. May.1992.
- (37) "Torsion Tests On Wire", A. Robongi, Wire Industry, June 1989.

- (38) "Wire Inspection by Eddy Current", L.A.Darell, A.J.Crisein, Wire Industry, Feb.1999
- (39) "Testing for Ferrous Inclusions", T.Eirspanier, Wire Industry, Feb.1988.
- (40) "Combined Eddy Current and Magnetic Inclusion Testing of Nonferrous Wire for Cracks and Ferrous Inclusion", P.W. Sarsieri, Wire J.Int.,Oct.1988.
- (41) "Development of a Quantitative Evaluation of Dusting on CopperRod", V.Sinha, SCR User Meeting, 1993, Atlanta.
- (42) "Rod Dust Control At Amrod", Amrod Company, SCR User Meeting, 1993, Atlanta.
- (43) "Manufacturing Technology", Volume 2, Engineering Process, J.M.Alexander, R.C.Brewer, G.W.Rowe, Ellio Horwood Limited, Chickester,1987.
- (44) "Manufacturing Properties of Materials", J.M.Alexander, D.Van Nostramd, Company Ltd. 1963, London.
- (45) "Encyclopedia of Materials Science and Engineering", M.B.Bever, Volume Perganon Press, 1986, USA.
- (46) "Mechanical Metallurgy", Dieter G.E., Second Edition, Mc Graw-Hill Company, 1976, New York.
- (47) "Production Technology", G.G.Thomas, Oxford University Press, 1970.
- (48) "Manufacturing Analysis", N.H. Cock, Addison-Wesley Series, 1966, USA.
- (49) "Manufacturing Engineering and Technics", S.Kulpakjiur, Addison-Wesley Publishing Company, 1995, USA.
- (50) "Introduction to Manufacturing Processes", Schey J.A., McGraw Hill Book Company, London 1988.
- (51) "Mechanical Working of Metals", Mc Millan Co Ltd. 1964, London.

(52) "Non-Ferrous Wire Handbook", Volume 2: Bare Wire Processing, The Wire Association International, 1981, USA.

(53) "Wire Drawing with Natural and Polycrystalline Diamond", Martin Jennings, De Beer, Industrial Diamond Division, Wire, Feb. 1988.

(54) "Tungsten Carbide Dies Designed by Wire Technology", R. Phillieps, J.G. Vijapure, A.D. Bhojwani, Wire Industry, Dec. 1980.

(55) "Wire Drawing Dies and Die Working Equipment", K.G. Eder, Wire Industry, Oct. 1986.

(56) "History of and New Trends in Wire Drawing Dies", K. Eder, Wire Industry, Nov. 1981

(57) "Development Tendencies in Copper Drawing Compounds", R. Zinnermann, G.H. Geiger, Wire, Jan. 1992.

(58) "Copper Wire Drawing Emulsion", H. Fischbach, Wire Industry, Nov. 1985.

(59) "Copper Drawing Agents-Some New Ideas", G.H. Geiger, Wire J. Int. May.

(60) "Basic Principles of Wire Drawing", L. Persson, P. Enghay, Wire Industry, Oct. 1996.

(61) "Wire Drawing", Worked Example, in Metalworking, G.J. Richardson. D.N. Hawkins, C.M. The Institute of Metals, 1985, London.

(62) "Drawing of Rod and Wire, Encyclopedia of Materials Science and Engineering", M.B. Bewer, Volume 2, Pergamon Press 1986, USA.

(63) "Flow Through Dies, Update 1989", B. Avitzun, Wire Ind. April, 1989.

(64) "Review of the State of the Art in the Study of Flow Through Conical Converging Die", Development in Drawing of Metal, The Metals Society, May. 1983, London.

- (65) "Wire Breaks In Copper", E.H. Chia, D.B. Cofer, O. Roberts, Wire Journal, Feb.1976.
- (66) "Copper Wire Breaks An Update", H. Chia, Proceeding of the 51st Convention of the Wire Association Int., Oct. 1981, Atlanta.
- (67) "Copper Break During Wire Drawing", T. Saito, K. Nakano, J. Togashi, H. Kayana, Proceeding of the 51st Convention of the Wire Association Int., Oct. 1981, Atlanta.
- (68) "Studies of Breaks in Ultra-Fine Wire", Y. Matsushita, Wire Ind., Aug.1985.
- (69) "The Problems of Material Defects in Super Fine Wire Drawing", F. Machie, IWMA Seminar, Feb. 1994.
- (70) "Wire Breaks During Copper Wire Production", S. Knupp, Wire, Feb. 1996.
- (71) "An Analysis of Wire Breaks During Drawing", S. Inove, The Furukawa Electric Review No.66, 1979.
- (72) "Drawability Index of Copper Wire", R.G. Anstey, Wire Ind. Sep. 1989.
- (73) "A Method for Monitoring and Determining the Drawability Index of Copper Wire", R.G. Anstey, Wire J.Int., Dec.1989.
- (74) "SEM and Wire Break Analysis", R. Adams, SCR User Meeting, 1996, Atlanta.
- (75) "Copper Wire Breaks Another View", C. Raskin, W.A.I.S. European Technical Conference Stresa-Italy, Oct. 1997.
- (76) "Material Defects – Problems In Fine Copper Wire Drawing", F. Machie, Wire Ind. Aug. 1994.
- (77) "Copper Wire Breaks Encyclopedia", H. Chia, G.R. Patel, Southwire Company, 1985, Atlanta.

(78) "Mechanics of Break", R.N. Wright, Proceedings of the 51st Annual Convention of the Wire Association Int., Oct. 1981, Atlanta.

(79) "Forge2 Solving Tomorrow's Forging Challenge Today", Instructional Manuel Handbook, Transvalor SA of Sophia, Technology Management Services Pty Limited, France.

(80) "Multi-line Wire Drawing-Quality Considerations", Tom Hardman, Prescott Rod Rollers, SCR User Meeting, Atlanta, USA, 1990.

(81) "Magnetic Inclusions and the Ferrous Detector", Ron Adams, Southwire Company, SCR User Meeting, Atlanta-USA, 1993.