TENSION AND TEMPERATURE COEFFICIENTS OF THE RESISTIVITY OF SOME METALS AND ALLOYS

BY

VICTOR KODZO MAWUENA

A THESIS SUBMITTED FOR THE DEGREE OF MASTER OF PHILOSOPHY
IN PHYSICS AT THE UNIVERSITY OF GHANA, LEGON

AUGUST, 1997

This work is dedicated to : Evelyn, Derrick and Fafa

DECLARATION

Except for references to the work of other people, this thesis is the work of the author's own research under the supervision of Professor J. K. A. Amuzu. It has neither in part nor whole been presented elsewhere for the award of a degree.

....
VICTOR KODZO MAWUENA
(STUDENT)

DATE : 6|8|98

....
PROF. J.K.A. AMUZU
(SUPERVISOR)

DATE : 6/8/98

PREFACE

I thank the Almighty God for making it possible for this work to come out successfully.

It was not easy coming out with this work. I owe Prof. J. K. A. Amuzu, my supervisor an incalculable debt of gratitude. I will always remember him for his encouragement and good supervisory skills.

I wish to thank my co-supervisors; Prof. R. D. Baeta and Dr. R. Kwadjo for their useful suggestions and contributions.

The kind assistance received from other lecturers of the department is greatly appreciated.

My appreciation also go to the laboratory technicians for their contributions in making this work a success.

This is an opportunity for me to express my sincere gratitude to my friends, colleagues and all others who in diverse ways have helped to bring this work to a successful completion.

Finally, I wish to thank Mr. N. F. Anku for typing this work neatly.

Victor Kodzo Mawuena

August, 1997

ABSTRACT

An attempt has been made to study the effects of tensile stress and temperature on the resistivity of some metals and alloys. The specimens include; copper, constantan, manganin, tantalum and minalpha. The strain coefficient of resistivity

$\frac{d\rho}{\rho d\epsilon}$, rate of increase of fractional resistivity with stress of resistance (gauge factor (K)) were determined for copper, constantan, manganin and tantalum.

For constantan, $\frac{d\rho}{\rho d\epsilon}$ is found to be highest for a sample of diameter 0.19 mm and lowest for diameter 0.31mm. Tantalum has the highest K-value hence it is the material expected to give relatively the highest strain sensitivity in strain gauges.

Minalpha has, however, shown the greatest extent of scatter.

LIST OF SYMBOLS USED AND THEIR MEANINGS

ϱ	resistivity
σ	Applied tensile stress
μ	Poisson's ratio
γ	Gruneisen's constant
K	Gauge factor (coefficient of strain sensitivity of resistance)
T	Temperature (^{0}C)
T_c	Curie Temperature

CONTENTS

CHAPTER ONE

INTRODUCTION

The principle on which strain gauges operate is the well established effect of the change in resistivity due to the imposition of stress. It is clear, therefore, that this present work which studies stress and temperature coefficient of the resistivity of constantan, manganin, copper, tantalum and minalpha is indeed a study of the strain gauge effect. In this introductory chapter, therefore, we devote some attention to reviewing this effect.

1.1 IMPORTANCE OF STRAIN GAUGES

Owing to advancing technology, structural parts require careful consideration for reasons of economy, safety, weight and appearance. This calls for an intensive knowledge of the behaviour of individual parts under stress. Essentially, it is important to investigate designed structural parts under all stress conditions. This is useful in all design work. By doing this, it becomes possible to match the various components of the entire construction. Various methods exist for obtaining such information. One such important method involves the use of the strain gauge. It is however, worth nothing that the diversity of strain gauges allows several applications even in other disciplines such as chemistry and medicine.

The use of strain gauges has several advantages over other methods of studying the effect of stress on structural parts. These are:

i. the comparatively simple handling;

ii. measurements are possible even under dynamic load;

iii. good and suitable adaptability to test problem;

iv. a large number of measuring systems are cheaply and readily installed;

v. largely free of of maintenance and having only little effect on the test object; and

vi. measurements can also be made on moving parts or in liquids.

By cementing a strain gauge onto the object to be tested, any strain in the test object is transmitted to the strain gauge.

The strain causes a proportional change in the resistance of the strain gauge. This change in resistance is related to the strain by a sensitivity-factor, K, which depends on the materials from which the strain gauge is made.

1.2 TYPES OF STRAIN GAUGES

There are four major types of strain gauges namely, (i.) flat wire strain gauges; (ii) wrapped around wire strain gauges; (iii) foil strain gauges; and (iv.) semi-conductor strain gauges.

Further classification is made according to their arrangement and application.

For wire gauges, wire is either wound around a piece of carrier material or flat in a meander form. With the former design, low grid dimensions are accomplished. However, its disadvantage lies in unfavourable creep behaviour. Due to high dynamic loads which may occur in use, the electrodes are welded to the measuring wire with great care. The use of the strip metal enables the weld to have a particularly high vibration resistance which consequently provides long life for itself (the weld) and the electrodes.

Two main disadvantages exist in forming a single wire into a grid. First, each conductor of the grid will lack complete strain transmission, since each turnaround, or endloop, acts like the end of a single shot bonded filament. Secondly, the endloop represents a small but significant length of bonded wire at right angles to the desired measuring axis, which will make the grid somewhat responsive to transverse strains. The loss in overall performance that results from forming a single long conductor into a grid is most significant for very short grids, since these contain a greater number of endloops, and the incompletely strained segments at the end of each line represent a greater percentage of the individual strand lengths.

1.3 TEMPERATURE COMPENSATION IN THE STRAIN GAUGE

As mentioned earlier, the bonded wire strain gauge is unique among scientific tools because of its versatility. Besides its fundamental use for measuring strains as such, the strain gauge can be adapted to measure loads, torques, pressures, vibrations, and numerous other physical quantities, limited principally by the imagination of the user.

Wire resistance strain gauges are now being employed at temperatures ranging from far below zero to close to the melting point of steel (Perry and Lissner, 1955), in locations of zero relative humidity and completely submerged in water and subjected to a number of other adverse environmental conditions.

Adequate temperature compensation is an absolute necessity for accurate measurement of static strains with all presently available bonded wire strain gauges. The need for temperature compensation of strain gauges arises from two factors.

First, there is the fact that the resistance of most wires changes with temperature. A second temperature effect occurs if the thermal coefficient of expansion of the strain gauge wire is different from that of the structure to which it is bonded. Thus, even if the strain gauge wire had a zero temperature coefficient of resistance, it would still be subject to false strain indications with temperature unless it had the proper coefficient of expansion. If such a gauge were constructed so that it was completely free of temperature errors when bonded to steel, it would be greatly in error if bonded to aluminium or some other metal with a different thermal coefficient of expansion.

Temperature compensation can be accomplished by installing a second strain gauge, often known as a "dummy" gauge, on an unstrained piece of the same metal as that to which the active strain gauge is bonded. If the two pieces of metal are subjected to the same temperature during testing, both gauges will experience identical thermal resistance changes. Perry and Lissner (1955) found that this is true whether resistance changes occur due to the temperature coefficient of resistance of the wire in the gauges or to the differential expansion existing between the gauges and the metal to which they are bonded.

1.4 THE SELF-TEMPERATURE-COMPENSATING STRAIN GAUGE

In some strain gauge installations where temperatures vary during the tests, it is impossible to subject the dummy gauge to the same temperature variations. In this case the self-temperature-compensating gauge is invaluable. This is a special type of gauge which has an extremely low temperature sensitivity when cemented to the particular metal for which it is designed. The gauge grid is constructed of two different wire materials in series. The lengths of the materials are proportioned so that the total increase in resistance with temperature (due to both thermal expansion and resistivity changes) of one material is very nearly cancelled by a decrease in the resistance of the other. For the dummy gauge in an installation of this sort it is possible to use any type of fixed resistance or mounted gauge which is maintained at a constant temperature throughout the test. It has been found experimentally, however, that, more accurate results are obtained if the dummy gauge is another self-temperature - compensated gauge.

1.5 SOME EARLIER WORKS

In their paper, "Measurement of the longitudinal piezo-thermoelectric effect in polycrystalline wires of the noble metals", May and Amuzu (1973) measured the thermo EMF produced between two wires of the same metal one of which was under tension which was within the elastic range. For the three wires (copper, silver and gold) used, it was found that the stretched wire becomes positive at the hot junction with respect to the unstretched wire.

The effect of tensile stress on the thermoelectric emf (TEMF) in copper, gold and silver (Amuzu 1981) revealed that there is a linear relationship between the TEMF and the temperature difference and also between the TEMF and the tensile stress.

The work on relative changes in the Fermi surfaces of the noble metals due to uniaxial tension (Amuzu and Addoli 1982) extended the earlier work by studying four more metals (Nb, Ta, Ni and Co) and also obtained the relative changes in the Fermi surface areas of Cu, Au and Ag. Comparison of the values of the relative changes in the Fermi surface areas per unit tensile stress with those of other workers using other techniques such as the de Haas-van Alphen (DHVA) effect shows that the Amuzu and Addoli values are much closer to other measurements on the neck than the belly of the Fermi surfaces.

In the measurements of the change in thermoelectric power of copper and silver under shear (Amuzu 1986), the shear piezo-thermoelectric coefficients found are close to those values predicted from Tinder's theory of the piezo-thermoelectric effects.

The variation of resistivity, ϱ with tensile stress, σ investigated for some metallic glasses (Amuzu et al 1990) showed that the resistivity of these specimens can be expressed as a power series function of the stress, $\varrho = \varrho_0 (1+D\sigma + E\sigma^2)$, where ϱ_0 is the resistivity of the unstressed specimen and D and E are constants.

In the study of the changes in coercivity, remanence and hysteresis power loss in some metallic glasses due to the application of tensile stress (Amuzu and Toworfe 1993), it was found that in the case of one of the glasses, $Fe_{40} Ni_{38} Mo_4 B_{18}$, the data suggests a discontinuity in the power loss versus annealing temperature curve. It has been suggested that the discontinuity indicates a two-stage relaxation process.

1.6 THE PRESENT WORK

In the present study, we have investigated the effect of both tensile stress and temperature on the resistivity of certain alloys. We have obtained the K-values for these alloys in an attempt to decide whether they would make good strain gauges. The materials chosen for the study are simply those which are available to us. Also, we have looked at the response of our specimens to temperature changes. In this case, however, too much reliance may not be placed on our findings since our set-up lacked a temperature controller for accurate control of the temperatures at which measurements were taken. Notwithstanding this, we have gained some insight into the way resistivity (which arises from the scattering of electron waves at the discontinuities characteristic of alloys) behaves at low and high temperatures. These findings are presented in Chapter Four. In the next chapter, we present the effect of stress and temperature on the resistivity of metals and alloys.

Chapter Three deals with the apparatus, materials and experimental procedures of this work.

CHAPTER TWO

THE EFFECT OF STRESS AND TEMPERATURE ON THE RESISTIVITY OF METALS

2.1 THE EFFECT OF STRESS ON THE RESISTIVITY OF METALS

The change in electrical properties of metals under stress was first investigated by Thompson (later Lord Kelvin, 1856), and described by him in a paper entitled "The Electrodynamical Qualities of Metals".

Tomlison (1883), at Lord Kelvin's suggestion investigated extensively the subject since Lord Kelvin's apparatus was not sensitive and could not provide reliable results.

Bridgman (1922; 1923; 1925) after working on the pressure coefficients of resistance made an extension to study the effect of change in electrical properties of metals under stress.

Measurement of the variation of electrical resistivity of metals with elastic deformation in different crystallographic directions by Druyvesteyn (1951) uncovered the phenomenon which is today utilized in the operation of electrical resistance strain gauges.

The change in electrical resistance due to strain is partly due to

i the geometrical changes taking place in the deformed body; and

ii. the physical changes within the metal itself.

For a metallic wire stretched longitudinally, these two factors are related by the following equation :

$$\frac{dR}{Rd\epsilon} = (1 + 2\mu) + \frac{d\rho}{\rho d\epsilon} \quad \text{\_\_\_\_\_\_ (2.1)}$$

where R is the total resistance of the wire, ρ its specific resistivity, ϵ the strain, and μ Poisson's ratio. $\frac{dR}{Rd\epsilon}$ is called the coefficient of strain sensitivity of resistance, or Gauge factor, and $\frac{d\rho}{\rho d\epsilon}$ the strain coefficient of specific resistivity.

The term, $(1 + 2\mu)$ denotes the purely geometrical effects of the deformation and the second term, $\frac{d\rho}{\rho d\epsilon}$ the physical one.

2.2. EFFECT OF DIMENSIONAL CHANGE ON THE RESISTANCE OF A WIRE UNDER STRAIN

As already indicated the effect of stress on resistivity is today utilized in the operation of resistance strain gauge. For any type of gauge there is a definite relation between strain and fractional change of resistance which can be expressed by

$$\frac{\partial R}{R} = K\frac{\partial l}{l} \quad \text{\_\_\_\_\_\_\_\_ (2.2)}$$

where $\frac{\partial R}{R}$ is the fractional change in resistance, $\frac{\partial l}{l}$ is the strain, and K is a constant known as the gauge factor or strain-sensitivity factor. Its value for a particular gauge depends on :

i. dimensional change in gauge wire due to strain;

ii. change in the resistivity of the gauge wire with strain;

iii. geometrical arrangement of gauge winding; and

iv. orientation of gauge axis relative to principal axes of strain.

The nominal value of a gauge factor refers to a property of the gauge placed along one of the principal axes of stress, the other principal stress being zero, that is, a gauge placed along the axis of pull of specimen in simple tension.

If l and A are the length and cross-sectional area of the wire, then $R = \frac{\rho l}{A}$

Also, $\delta R = \frac{\partial R}{\partial l}\delta l + \frac{\partial R}{\partial A}\delta A$

$$= \frac{\rho \delta l}{A} - \frac{\rho l \delta A}{A^2}$$

$$\frac{\delta R}{R} = \frac{1}{R}\left[\frac{\rho \delta l}{A} - \frac{\rho l \delta A}{A^2}\right]$$

$$= \frac{A}{\rho l}\left[\frac{\rho \delta l}{A} - \frac{\rho l \delta A}{A^2}\right]$$

$$= \frac{\delta l}{l} - \frac{\delta A}{A}$$

But $\frac{\delta A}{A} = -2\left[\frac{\delta l}{l}\right]\mu$, where μ is Poisson's ratio for the material of the wire, so that $\frac{\delta R}{R} = \frac{\delta l}{l}(1 + 2\mu)$ ________ (2.3)

Hence, due to change of dimensions, the ratio of fractional resistance change to fractional strain is $(1 + 2\mu)$. It is not surprising, therefore, that this factor is closely related to K as we now show in the derivation of the relationship between

$\frac{dR}{d\epsilon}$ and $\frac{d\rho}{d\epsilon}$

2.3 DERIVATION OF GAUGE (OR K-) FACTOR

Consider that a length of wire l is stretched so that the increase in length is Δl and the strain developed is ϵ. There is a transverse contraction so that the change in the radius of the cross-section is Δr (see fig. 2.1). Since $l + \Delta l > l$, it follows that $\Delta l > 0$. Similarly, since $r + \Delta r < r$, $\Delta r < 0$.

Again,
$$A = \pi r^2 ; \quad dA = 2\pi r dr$$
$$\epsilon = \frac{\Delta l}{l} ; \quad d\epsilon = \frac{dl}{l}$$
$$\mu = \frac{l\Delta r}{r\Delta l} ; \quad R = \frac{\rho l}{A}$$

By definition,

$$\frac{dR}{R} = d(\rho l/A)/\rho l/A$$
$$= \left[\frac{\rho dl}{A} + \frac{ld\rho}{A} - \frac{\rho l dA}{A^2}\right] \cdot \frac{A}{\rho l}$$
$$= \frac{dl}{l} + \frac{d\rho}{\rho} - \frac{dA}{A}$$
$$= \frac{dl}{l} + \frac{d\rho}{\rho} + \frac{2dr}{r}$$
$$= \frac{dl}{l} + \frac{d\rho}{\rho} + \frac{2\mu dl}{l}$$
$$= \frac{dl}{l}(1+2\mu) + \frac{d\rho}{\rho}$$
$$= d\epsilon\,(1 + 2\mu) + \frac{d\rho}{\rho}$$

$$\therefore \frac{dR}{Rd\epsilon} = (1 + 2\mu) + \frac{d\rho}{\rho d\epsilon} \quad \text{--------} \quad (2.1)$$

$\frac{dR}{Rd\epsilon}$: Gauge (or K-) factor; Coefficient of strain sensitivity of resistance.

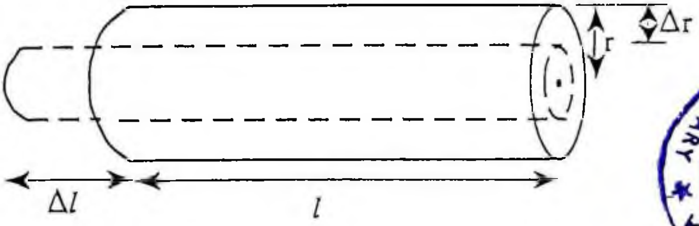


Fig.2.1: Diagram of a stretched wire

$\frac{d\rho}{\rho d\epsilon}$: Strain Sensitivity of specific resistivity

2.4 CALCULATION OF STRAIN COEFFICIENT OF RESISTIVITY FOR METALS

The strain coefficient of resistivity may be calculated from

$\frac{d\rho}{\rho d\epsilon} = 1 + 2\gamma(1-2\mu)$ ------- (2.4) where μ is Poisson's ratio and γ the Gruneisen's constant.

Many properties of certain groups of metals such as copper, gold and silver can be semi-quantitatively treated as the properties of a hypothetical degenerate electron gas. One often assumes that electrons in a metal can be treated as noninteracting particles moving in some kind of average potential of the periodicity of the lattice. This potential can be considered as being weak in the sense that the distribution of energy levels is determined largely by the kinetic rather than the potential energy. The electrical resistivity of a metal can be considered as a function of two variables, the mean free path l of the electrons and the effective number n of free electrons;

$$\rho \sim m/ln$$

Assuming that the effective mass m of an electron is constant, we obtain the following expression for the coefficient of strain sensitivity :

$$\frac{d\rho}{\rho d\epsilon} = -\frac{dl}{ld\epsilon} - \frac{dn}{nd\epsilon} \text{ ----------- (2.5)}$$

If a weak potential is assumed, then the energy E of the electrons can be adequately evaluated by the following equation:

$E = (h^2/2m)k^2$, ----------------(2.6) where k is the wave vector and ħ, the Planck's constant. The number of free electrons

$$n = \frac{2}{\pi} . \frac{m}{\hbar^{2}} \left[\frac{\delta E}{\delta k}\right]_{k_{max}}$$

or, from Eq (2.6), $n = (2\pi)\,k$

and $\frac{dn}{nd\epsilon} = \frac{dk}{kd\epsilon}$

The wave vector $k \sim 1-\beta\epsilon$ where β has different values for different metals but always is of the order of unity, therefore

$$\frac{dn}{nd\epsilon} \sim -1 \quad \text{---------} \quad (2.7)$$

The change of the mean free path l can be evaluated from the relationship $l \sim 1/\langle x^2\rangle_{AV}$, where $\langle x^2\rangle_{AV}$ denotes the mean square of the displacement of the vibrating atom. It is easy to show (Mott and Jones, 1936) that, for $T > \theta$, $\langle x^2\rangle AV \sim 1/\theta^2$; therefore $l \sim \theta^2$. On the other hand, the change of the characteristic temperature θ with change of volume V is $\frac{d\ln\theta}{d\ln v} = -\gamma$, where γ is Gruneisen's

Constant, conveniently calculated from the following relationship:

$$\gamma = \frac{\propto Cv}{x\ V_0}$$

where $\propto$ is the volume Coefficient of thermal expansion, Cv the molar specific heat at Constant volume, x compressibility and V_0 the atomic volume.

If we assume that electrons in metals are not constrained to any specific path, then, as $d\ln V = (1 - 2\mu)\, d\epsilon$,

$$\frac{dl}{ld\epsilon} = \frac{2d\theta}{\theta d\epsilon} = -2\epsilon\gamma(1 - 2\mu) \quad \text{-------} \quad (2.8)$$

Equations (2.5), (2.7) and (2.8) yield

$$\frac{d\rho}{\rho d\epsilon} = 1 + 2\gamma\,(1-2\mu) \quad \text{--------} \quad (2.4)$$

Bridgman (1925) states that the difference in longituditional and transverse coefficients of strain sensitivity seems to indicate that the mean free path of the electrons must be somewhat constrained. Assumption of a fully constrained path does give too high longitudinal effects and does not account satisfactorily for the variety of the transverse effects.

2.5 TEMPERATURE DEPENDENCE OF RESISTIVITY OF METALS

In spite of the very high density of conducting electrons in metals, the contribution to the resistivity of "simple" metals from electron-electron collisions is negligible. There are two reasons for this:

i. When all the conduction electrons are alike, momentum is conserved during any electron-electron N-process so that such collisions do not in anyway attenuate the total electric current;

ii. on the other hand, it is possible for electrons to loose momentum to the lattice via electron- electron U-processes. However, the net effect of these processes is also very small, partly because the scattering cross section for screened coulomb interactions, Σsc, is intrinsically small, and partly because the application of the exclusion principle requires that only electrons close to the Fermi energy take part in this process. In any scattering event both the initial and final electron states are confined to a narrow range of energy within kT of the Fermi energy, so that the effective electron-

electron scattering cross section Σee is given by $\Sigma ee \sim \Sigma sc \left[\frac{kT}{E_F}\right]^2$, where E_F is the Fermi energy, k, the Boltzmann's constant and T, the temperature. As a consequence of $\Sigma ee \sim \Sigma sc\left[\frac{kT}{E_F}\right]^2$, it is clear that any electrical resistivity ϱ_{ee} arising from electron-electron scattering must vary as T^2. It is, therefore, generally accepted that the criterion for the existence of such scattering is the presence of a T^2 term in the low-temperature resistivity.

For transition metals, components of resistivity varying as T^2 have been seen at low temperatures in no fewer than eighteen of the twenty-four elements studied by Volkenshtein et al 1971, and it is clear, as first pointed out by Barber (1937), that some form of electron-electron scattering is most important. Mills and Lederer (1966) and Schindler and Rice (1967) have shown that (as might be expected) electron-paramagnon scattering at very low temperatures also results in a resistivity varying as T^2, and they therefore attribute the observed temperature dependence in palladium and platinum and their alloys to that source. Their interpretation is strongly supported by measurements on the Pd-Ni system. In these alloys, both the magnetic susceptibility and the coefficient of T^2 in the electrical resistivity rise rapidly with increasing nickel concentration. Lederer and Mills (1968) show how these observations can be interpreted on the basis of local spin-density fluctuations at the impurity (nickel) sites additional to the uniform spin fluctuations in the palladium host.

In the last thirty years or so interest has centered on the behaviour of ρ and S, total thermopower within a few degree of the Curie temperature, T_c. The reason is that the magnetic phase transition is now recognized as a critical phenomenon (Fisher, 1967), with the specific heat, C exhibiting a lambda anomaly - that is, divergent behaviour - at the critical point, T_c (Handler et al 1967).

In addition, it has also been shown that both $\frac{d\rho}{dT}$ (Craig et al 1967) and $\frac{ds}{dT}$ (Tang et al 1974; Piotrowski et al 1974) exhibit lambda peaks at T_c.

In the neighbourhood of T_c the temperature variation of C, $\frac{d\rho}{dT}$ and $\frac{ds}{dT}$ can all be represented by the same type of (divergent) empirical law. For example, in the case of resistivity, the law is $\frac{1}{\rho C} \frac{d\rho}{dT} = \frac{A}{\lambda} \frac{-\lambda}{\delta} -1 + B$ where $\delta = (T - T_c)/T_c$, ρ_c is the resistivity at the Curie point, and A, B, and λ are constants. In general, data are best for $T > T_c$, and it has been shown that for pure Ni, λ^{+} (i.e., λ for $T > T_c$) is ~ 0.1 for each of the three variables C, $\frac{d\rho}{dT}$, and $\frac{dS}{dT}$. This divergence of the derivative has been explained by Fisher and Langer (1968) on the basis of scattering from short-range spin fluctuations.

2.6 RESISTIVITY AND THE CRYSTAL LATTICE

For crystals having axial symmetry, there result two independent constants, ϱ_{11} and $\varrho_{\perp}$, the resistivities parallel and perpendicular to the principal axis. The resistivity ϱ_{θ} in a direction making an angle θ with the principal axis is then

$$\varrho_{\theta} = \varrho_{11} \cos^2\theta + \varrho_{\perp} \sin^2\theta$$

which agrees with experimental observation and was first put forward by Voigt in 1910.

The theory has been successful in explaining most of the phenomena related to metallic conduction and we may, in the light of it, consider what sort of information resistivity measurements are likely to supply concerning other features of the behaviour of metals. It is clear that differences in resistivity between two samples of metals or changes in the resistivity of a given sample during the course of any treatment to which it may be subjected must be due to differences in the energy and structure and the manner in which the states are occupied, or in the pattern of irregularities or some combination of these causes. The correct interpretation of the cause of these differences may then, in many cases, provide significant information concerning the differences between the samples or the process of change in a single sample.

2.7 LATTICE IRREGULARITIES: EFFECT OF TEMPERATURE

Let us consider the irregularities in lattice structure which cause electrical resistance in a metal. Taking first the simplest case, that of a pure metal in the annealed condition, we find that if the temperature of such a sample is reduced, the resistivity decreases steadily and approaches zero as the absolute zero of temperature is approached. The resistance must therefore be due to irregularities associated with temperature, as a result of the disturbances of the lattice caused by thermal oscillations of the atoms. It is found experimentally that at ordinary temperatures, the resistivity is very roughly proportional to the absolute temperature. Theoretical treatment of the scattering of the electrons by collisions with the oscillating atoms lead to a result in agreement with this observation. The scattering probability is proportional to the mean square of the amplitude, $\overline{x^2}$, of the atomic oscillations, which, at a temperature T, above the characteristic temperature θ, is given by $\overline{x^2} = h^2T/4\pi^2kM\theta^2$, where M is the atomic mass, h Planck's constant and k is Boltzmann's constant. Hence the resistivity, which is proportional to the scattering probability, may be expressed as

$\varrho = \frac{C'T}{M\theta^2}$, where C', a constant characteristic of the metal concerned, is a measure of the resistivity for a given amplitude of atomic oscillations. C', therefore, is the factor which depends upon the detailed nature of the electron energy band structure and is the fundamental quantity for comparison of behaviour of electrons in different metals.

2.8 DISSOLVED ATOMS AND MATTHIESSEN'S RULE

Another cause of irregularities in the lattice which leads to scattering of the electrons is the presence of impurity atoms. If the temperature of a sample of a dilute solid solution is reduced, its resistivity decreases but it does not approach zero at absolute zero of temperature; it approaches a limiting residual value. This is the resistivity due to the irregularities in the periodicity of the lattice field caused by the foreign atoms.

Matthiessen expressed the fact that in such metals the total resistivity was the sum of the temperature-dependent resistivity ϱ_T of the pure metal and a temperature independent resistivity ϱ_R, as $\varrho = \varrho_R + \varrho_T$. This implies that the foreign atoms do not alter the effective number of free electrons, the energy band structure or the characteristic temperature of the metal and their thermal vibrations scatter the electrons in the same way as those of the parent metal. The rule is found to hold in dilute solutions in general though there are exceptions. If the rule holds, the temperature variation of resistivity

$$\frac{d\varrho}{dT} = \frac{d\varrho_T}{dT},$$ which is independent of composition,

that is, the resistivity-temperature curves for different compositions should all be parallel. Alternatively, the temperature coefficient of resistivity is

$$\alpha' = \frac{1}{\varrho}\frac{d\varrho}{dT} = \frac{1}{\varrho}\frac{d\varrho_T}{dT}$$

Hence $\alpha'\rho = \frac{d\rho_T}{dT}$, a constant for a given parent metal. This is an alternative form of expressing Matthiessen's Rule which is particularly useful since, what is usually measured is the resistance R of a specimen and this depends upon the dimensions and quite possibly internal cracks or voids. However, the temperature coefficient of resistance is independent of dimensional effects of this nature,

$$\alpha' = \frac{1}{\rho}\frac{d\rho}{dT} = \frac{1}{R}\frac{dR}{dT},$$

so that when Matthiessen's Rule is known to apply, measurement of the temperature coefficient of resistance of a specimen will serve to determine its resistivity unambiguously.

The resistivity ρ_R due to dissolved atoms is usually large. ρ_R many be as large as ρ_T at room temperature for one per cent of impurity. Thus resistivity measurement may be used as a valuable check on purity.

The effect varies in magnitude over a considerable range for different solutes in different metals. Norbury (1921) compared the effect of one per cent of different solutes in a number of parent metals, and found that in general the increase in resistance was greater the greater the difference in valency between solute and parent.

Linde (1931, 1932) showed that the increase was approximately proportional to the square of the difference in valencies. This has been simply explained by Mott (1936).

CHAPTER THREE

APPARATUS, MATERIALS AND EXPERIMENTAL PROCEDURES

3.1 INTRODUCTION

The experimental methods and procedures that have been employed in this work are described in this chapter.

The main work involves the measurement of the effect of stress on resistivity and that of temperature on resistivity.

The main investigation was carried out using the resistivity-stress (ρ-σ) apparatus and the resistivity-temperature (ρ-T) apparatus. In what follows, we describe both sets of apparatus. We also present the particulars of the materials used and detailed descriptions of experimental procedures adopted.

3.2 THE RESISTIVITY-STRESS (ρ-σ) APPARATUS

Figure 3.1 is the diagram of the stress-resistivity apparatus. The wire specimens were stretched in a simple holder. One end of the specimen, D was clamped. It was then passed over a small pulley at A, so that weights could be hung on the free end, Q. L is the actual length of specimen under test. Electrical connections were made at B and C by careful soldering. E is the carrier frequency bridge which is a wheatstone bridge. The metallic wire specimen BC was connected in one arm of the bridge and a resistance box R in series with a variable resistance r was connected in the other arm. Figure 3.2 is a circuit diagram of the wheatstone bridge formed by the resistance R_{BC} of the specimen BC,

Fig. 3.1 : Diagram of the resistivity-stress apparatus for the application of tensile stress to specimen

A - Pulley

E - Carrier frequency bridge

BC - Specimen

R - Resistance box

H, I - Pulleys

P - Meter bridge

J - Jockey

T - Knob

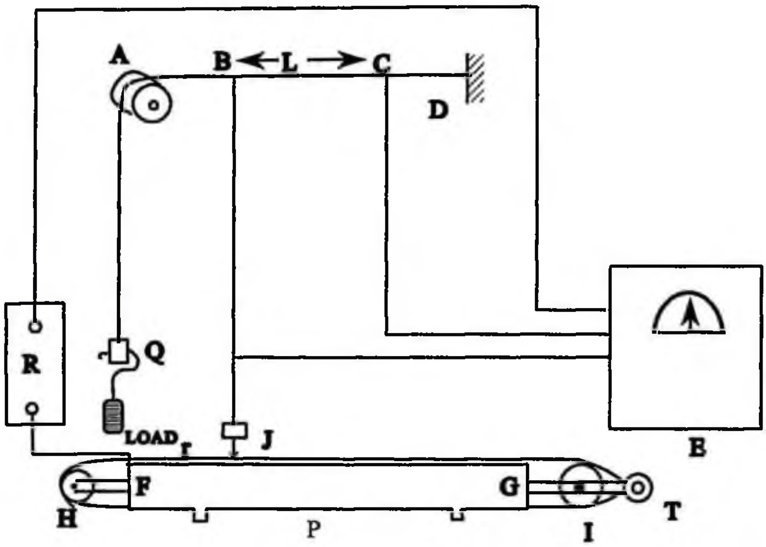


Fig.3.1: Diagram of the resistivity-stress apparatus.

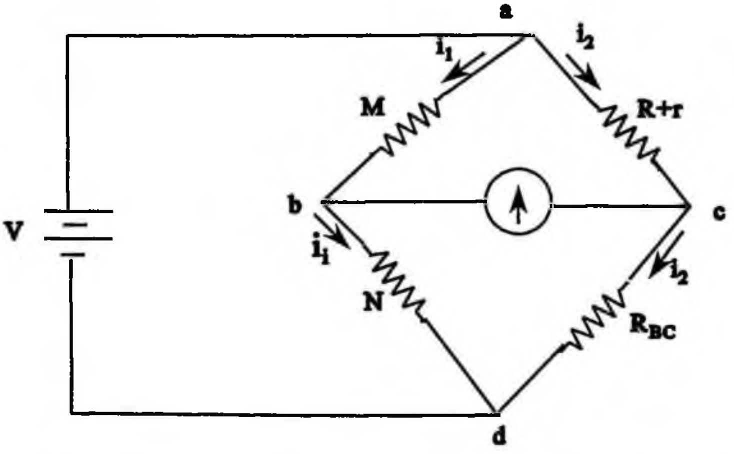


Fig.3.2: Circuit diagram of the measuring section of the resistivity-stress apparatus.

the resistance (R+r) and the resistances M and N in the carrier frequency bridge. r is the resistance of the length of wire FG between F and the position of a jockey J. J is moved by the help of a small wheel attached under its holder. The contact of J slides on FG.

This contact is made very sharp in order to reduce the surface of contact between J and the resistance wire FG. A 2-kg load is rigidly fixed onto the top of the jockey holder. Without this load, the contact between the tip of the jockey and FG is rather uncertain (as indicated by the meter on E). Another significant feature of our set-up is the system of motion of the jockey; much like the tuning system in a radio. This consists of a chord which goes over pulleys H and I, fixed at the ends of P. This chord is also attached to the jockey holder. This arrangement allows the jockey to be moved along FG by means of a knob T. This system of driving J is necessary because initial trials involving moving J with the hand proved very unreliable and unsatisfactory.

3.3 THE RESISTIVITY-TEMPERATURE (ρ-T) APPARATUS

The ϱ-T apparatus consists of a power source V_0,an ammeter A, the sample S of resistance R_s in series with a high resistance R' of the order of $10^5\Omega$. R' is necessary because since it is high, most of the voltage drop in the circuit will be across it hence it will swamp the voltage drop in the circuit and allow V_s to be obtained accurately. In the absence or R', the voltage drop in the connecting wires in the circuit may even be more than that across

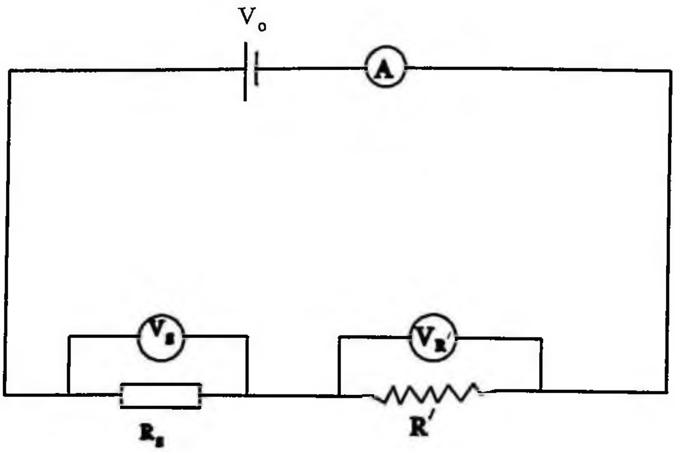


Fig.3.3: Circuit diagram of resistivity-temperature apparatus.

the sample and thereby giving inaccurate results.

The sample is placed in an oven made of ceramic material.

3.4 CONSTRUCTION OF THE LID OF THE OVEN

It was necessary to improvise a lid for a small electric oven ($2.47 \times 10^{-4} m^3$) which was used for our temperature studies. Clay is moulded in the form of a cylindrical bowl with an open end that covers perfectly the heating base of the oven.

A hole which is large enough only to contain a mercury-in-glass thermometer is centrally made at the closed end of the bowl by carefully pushing through the unbaked clay a solid cylindrical glass rod which is slightly bigger in diameter than the thermometer.

The bowl was then baked in a bigger oven to ensure that it is hardened.

The oven is connected to a Variac which regulates the voltage to it.

3.5 MATERIALS

These are metallic wires of diameters ranging from 0.09mm to 0.38mm. They include copper, manganin, constantan, tantalum and minalpha. These were all obtained from our laboratory stock.

copper : The London Electric Wire Company and Smiths Limited

manganin: W.B. George and Decker Limited of London.

constantan: The Temple Electrical Company Limited of London.

Information on the manufacturers of tantalum and minalpha were not available.

Constantan, manganin and minalpha are alloys with compositions as follows :

constantan :	copper and nickel
manganin :	copper, nickel and manganese
minalpha :	copper, manganese, chlorine, aluminuim and sodium.

3.6 EXPERIMENTAL PROCEDURES

In this section, the various experimental procedures have been described.

3.7 MEASUREMENT OF CHANGE OF RESISTIVITY (ρ) WITH STRESS (σ)

The resistances of the wire specimens, their dimensions and the resistance of wire FG (Fig. 3.1) were measured at room temperature, 300K.

The carrier frequency bridge E was balanced and allowed to stabilize for at least thirty (30) minutes. After this period, loads of increasing magnitudes were applied to the wire specimens at Q. The resultant increase in the resistance of the specimen due to the application of this stress puts the bridge out of balance. The corresponding lengths Δl of the resistance wire FG along which the jockey should move in order to bring the bridge back to balance were measured. Each of the measurements for the various loads was repeated and the average values evaluated. Each of the remaining specimens was fixed up in turn in the set up.

Suitable values of R and r were selected in each case in order to balance the bridge initially and measurements were made on each as described above.

3.8 MEASUREMENT OF CHANGE OF RESISTIVITY (ρ) WITH TEMPERATURE (T)

The specimen which is wound round a porcelain material is placed in an oven with the ends of the specimen connected in the circuit. The oven and the power source are switched on. The Digital Multimeter is used to measure V_R', the voltage across R'; V_S' the voltage across the sample and the current read from the ammeter.

The temperature of the specimen is measured at intervals of 15^0C. Thus the resistance, R_S of the specimen at various temperatures is obtained from which the corresponding resistivities are computed.

This process is repeated for all the samples. There was no temperature controller available to us hence an error of $\pm 3^0$C is obtained in obtaining the resistivity for a particular temperature read.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

INTRODUCTION

As pointed out in the proceeding sections, the main focus of this study is the response of some selected metals and alloys to stress. In particular we are concerned with the effect of uniaxial stress and temperature on the resistivity of the materials. In order to carry out these studies we have had to adapt equipment such as the meter bridge for our purposes. Also we had to construct some components to be used with an electric oven.

In this chapter we present these results of our studies. First we discuss the effect of stress on resistivity to be followed by the effect of temperature on resistivity. We shall endeavour to rationalize our findings by comparing them with the work of other researchers.

4.1 THE BEHAVIOUR OF METALS UNDER STRESS

In his work, Kuczynski (1953) studied the fractional change of electrical resistance, $\frac{\Delta R}{R}$ as a function of the strain increment, $\Delta\epsilon$ for various nickel samples. From these studies, he was able to calculate the strain coefficient of specific resistivity, $\frac{d\rho}{\rho d\epsilon}$. The results illustrate that even in the elastic range, the coefficient is not constant. Indeed it changes from a negative value for strains ranging from 0.2×10^{3} to 1.0×10^{3} to a positive value for ranges 1.0×10^{3} to 6.0×10^{3}. A similar behaviour was observed by

McKeehan (1930).

In this work, we have not been able to apply strains in the range of 0.2×10^3 to 0.9×10^3 so that we are only concerned with the positive coefficients.

4.2 RESULTS FROM THE PRESENT STUDY

Fig 4.1 illustrates the stress dependence of fractional resistivity for manganin, copper, constantan and tantalum. For constantan of diameters 0.19mm and 0.31mm, the graphs of $\frac{\Delta\rho}{\rho}$ versus σ are almost parallel to the σ-axis. This observation is also true for tantalum of diameter 0.235mm. In general, as the tensile stress increases, the fractional resistivity also increases.

Since a large part of the resistivity of alloys may be attributed to scattering of electron waves by irregularities arising from the introduction of foreign atoms, perhaps stretching the lattice may lead to further disorder in the packing of the different atoms, hence the increase in resistivity (Bridgman 1931).

In Table 4.1 we list the slopes of the curves in Fig. 4.1. From the table, the slope of the stress-fractional resistivity plot increases with decreasing diameter for copper and manganin. However, it is the reverse in the case of constantan as the slope increases with increasing diameter of the wire.

Only one diameter of tantalum was available to us for study so that in this case no comparison is possible.

Fig. 4.1 : Stress dependence of fractional resistivity for manganin, copper, constantan and tantalum

RESIS 1 - copper of diameter = 0.09mm

RESIS 2 - constantan of diameter = 0.19mm

RESIS 3 - copper of diameter = 0.105mm

RESIS 4 - manganin of diameter = 0.105mm

RESIS 5 - manganin of diameter = 0.38mm

RESIS 6 - tantalum of diameter = 0.235mm

RESIS 7 - constantan of diameter = 0.31mm

Fig 4.1: STRESS DEPENDENCE OF FRACTIONAL RESISTIVITY

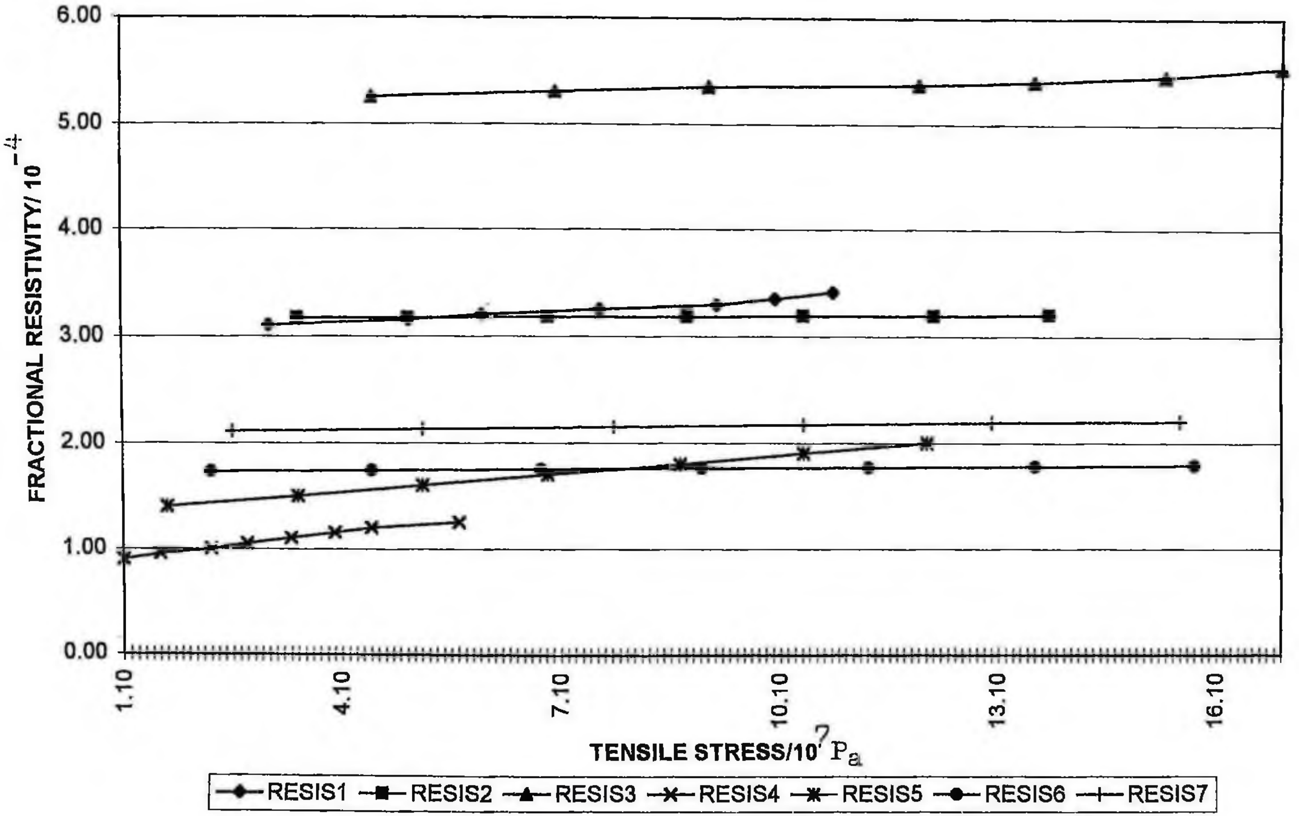


TABLE 4.1 : RATE OF INCREASE OF FRACTIONAL ϱ WITH σ AND DIAMETERS OF MATERIALS

MATERIAL	SLOPE/ 10^{-13} $m^4A^{-2}s^{-1}$	DIAMETER $d/10^{-2}$mm
MANGANIN	8.70	10.50
	5.77	38.00
COPPER	3.28	9.00
	2.19	10.50
CONSTANTAN	0.77	31.00
TANTALUM	0.52	23.50
CONSTANTAN	0.29	19.00

We now consider the Young's moduli of the materials studied and the slopes obtained.

TABLE (4.1)' : YOUNG'S MODULI OF MATERIALS

MATERIAL	RATE OF INCREASE OF FRACTIONAL ϱ WITH $\sigma/10^{-13}$ $m^4A^{-2}s^{-1}$	YOUNG'S MODULUS, $y/10^{10}$ Nm^{-2}
MANGANIN	8.70	12.4
COPPER	3.28	(10.5 to 13.0)
CONSTANTAN	0.77	16.3
TANTALUM	0.52	18.6

Table (4.1)' illustrates this

In table (4.1)', we compare the rate of change of fractional ϱ with σ with the respective Young's modulus values of the materials studied. We note that when the rate of increase of fractional resistivity with stress of the materials are arranged in the order of decreasing rate, the Young's moduli follow an order of increasing value. This is what must be expected since Young's modulus measures the stiffness of the material. The stiffer a material, the less is its response to an applied stress. This is a rule-of-thumb test for the validity of our experiments. This same test was employed by Amuzu (1980) in validating his work on the effect of stress on the thermoelectric emf of some metals.

Hence for the same load, manganin and copper are stretched more than constantan and tantalum.

4.3 STRAIN COEFFICIENT OF SPECIFIC RESISTIVITY $\frac{d\varrho}{\varrho d\epsilon}$

In this section, the strain Coefficients of specific resistivity. $\frac{d\varrho}{\varrho d\epsilon}$ of the materials of our work and those obtained from other investigations are discussed. The strain Coefficients of specific resistivity, $\frac{d\varrho}{\varrho d\epsilon}$ from this work are given in Table 4.2 below.

TABLE 4.2 : STRAIN COEFFICIENTS OF SPECIFIC RESISTIVITY FROM THIS WORK

MATERIAL	DIAMETER $d/10^{-2}$mm	$\frac{d\rho}{\rho d\epsilon}$
COPPER	9.0	1.24
	10.5	1.40
CONSTANTAN	19.0	1.50
	31.0	0.68
MANGANIN	10.5	1.21
	38.0	1.22
TANTALUM	23.5	1.45

From Table 4.2, $\frac{d\rho}{\rho d\epsilon}$ increases with diameter except in the case of constantan.

TABLE 4.3 : KUCZYNSKI'S

MATERIAL	DIAMETER $d/10^{-2}$mm	$\frac{d\rho}{\rho d\epsilon}$
COPPER	25.80	1.60
	12.85	1.55
	5.48	1.20
	2.61	0.90
	1.06	0.90
TANTALUM	12.42	0.30
TUNGSTEN	12.95	1.16
	1.42	1.16
COPPER-NICKEL (Cu-Ni) (Atom % Ni)		
1.08	25.30	1.54
	2.54	0.43
11.50	25.80	0.70
	2.69	0.80
45.00	25.60	0.3
72.00	25.60	-0.19
	2.64	-0.19
98.30	25.50	-13.06
99.50	25.50	-13.62
TOTAL	2.64	-8.12

Table 4.3 gives Kuczynski's results.

For copper $\frac{d\rho}{\rho d\epsilon}$ increases with diameter. Tungsten (W) has the same values of $\frac{d\rho}{\rho d\epsilon}$ (1.16) for two different diameters of wire.

For Copper-Nickel alloys, the $\frac{d\rho}{\rho d\epsilon}$ values depend on the atomic composition of Nickel in the alloy.

From these results, it is interesting to note that for the same diameter of wire but different atomic compositions of Ni in the Cu-Ni alloy, the $\frac{d\rho}{\rho d\epsilon}$ values are different. For a material of 72.0% Ni in Cu-Ni, the $\frac{d\rho}{\rho d\epsilon}$ values are the same (i.e. -0.19) for different diameters of wire.

Comparing the results of this work (Table 4.2) with those of Kuczynski (Table 4.3), we find that there is a fair agreement between the cases for which comparison is possible.

For example, for copper, our work and Kuczynski's studied two specimens whose diameters are close enough to allow some comparison. The values of the diameters are 10.5×10^{-2}mm and 12.85×10^{-2}mm for our work and Kuczynski's respectively. The values of $\frac{d\rho}{\rho d\epsilon}$ for these are shown below :

Table 4.4 : THIS WORK AND KUCZYNSKI' WORK ON COPPER

MATERIAL	COPPER	
	DIAMETER/ 10^{-2}mm	$\frac{d\rho}{\rho d\epsilon}$
Kuczynski's	12.85	1.55
This Work	10.50	1.40

Clearly, the above results show that our measurements are probably accurate although our set-up is rather very simplified.

TABLE (4.4)' : EXTRACTS FROM TABLES 4.2 AND 4.3

	%Ni	Cu-Ni $d/10^{-2}$mm	$\frac{d\rho}{\rho d\epsilon}$
Kuczynski's	1.08	25.30	1.54
This Work	-	19.00	1.50

For 1.08 percentage composition of Ni in Cu-Ni (Table 4.3), $\frac{d\rho}{\rho d\epsilon}$ is 1.54 for a wire of diameter 25.30 x 10^{-2}mm. This compares very well with $\frac{d\rho}{\rho d\epsilon}$ of 1.50 for Constantan of diameter 19.0 x 10^{-2}mm from this work (Table 4.2).

Additionally, constantan is an alloy made of copper and nickel, we may conclude that Constantan of diameter 19.0 x 10^{-2}mm from our work consists of a very small amount of nickel.

As the amount of Ni in the Cu-Ni alloy (Table 4.3) increases, $\frac{d\rho}{\rho d\epsilon}$ becomes negative.

Again, we can make comparisons between our work and those of Bridgman, Rolnick and Kuczynski. Below is a tabulation to aid this comparison.

TABLE 4.5 : STRAIN COEFFICIENTS OF RESISTIVITY OF METALS (PRESENT WORK AND WORKS OF BRIDGMAN, ROLNICK AND KUCZYNSKI)

METAL	$\frac{d\rho}{\rho d\epsilon}$ (a)	$\frac{d\rho}{\rho d\epsilon}$ (b)	$\frac{d\rho}{\rho d\epsilon}$ (c)	$\frac{d\rho}{\rho d\epsilon}$ (d)
Cu	1.60	1.60	0.90 to 1.60	1.55
Al	2.62	-0.68	1.40	-
Co	0.37	-	0.84	-

a. refers to Bridgman's work

b. refers to Rolnick's work

c. refers to Kuczynski's work

d. refers to present investigation (our work)

From Table 4.5, $\frac{d\rho}{\rho d\epsilon}$ from the works of Bridgman, Rolnick, Kuczynski and our work for Cu agree very well. Unfortunately specimens of Al and Co were not available to us for study. The values for these specimens from the work of Kuczynski have been given in Table 4.3 to illustrate the point that these measurements can produce widely varying coefficients.

4.4 K - FACTORS

This section deals with gauge factors or K values obtained from our work for the various materials studied.

The gauge factor or $K = \frac{dR}{Rd\epsilon}$ is also called the coefficient of strain sensitivity of resistance. These K values are listed below.

TABLE 4.6 : K - FACTORS

MATERIAL	K
COPPER	3.02
CONSTANTAN	2.74
MANGANIN	2.88
TANTALUM	3.13

The value of K varies between 2 and 6 for metals; for semiconductor materials, values up to and above K = 180 are obtained. The sensitivity of a strain gauge is indicated by the K - factor. To achieve a high sensitivity, the K - factor must be as large as possible.

4.5 EFFECT OF TEMPERATURE ON RESISTIVITY

This section concerns the effect of temperature (T) on resistivity (ϱ). This aspect of the work has become necessary because strain gauges depend on temperature. The investigations of temperature dependence of resistivity of these metals and alloys is to enable us to determine their suitability for use in strain gauges.

This aspect of the work is a difficult one as there was no temperature controller available to us. Thus as mentioned in the experimental procedures, there is an error of $\pm 3^0$C in obtaining the resistivity of a particular temperature. This gives an error of about 10% at lower temperature readings to about 2% at higher temperature values.

In Fig. 4.2, graphs of resistivity against temperature for copper of two different diameters, constantan of diameter 0.23mm and manganin of diameter 0.105mm are shown.

In general, resistivity at lower temperatures is steady but increases as the temperature is increased. The bigger the value of R' in the resistivity-temperature apparatus, (Fig. 3.3), the higher the curve (Fig. 4.3).

Fig. 4.2 : Temperature dependence of resistivity for manganin, copper and constantan

RESI 1 – manganin of diameter = 0.105mm and R' = 315.0kΩ
RESI 2 – copper of diameter = 0.105mm and R' = 125.5kΩ
RESI 3 – copper of diameter = 0.105mm and R' = 105.0kΩ
RESI 4 – copper of diameter = 0.09mm and R' = 105.0kΩ
RESI 5 – constantan of diameter = 0.23mm and R' = 120.0kΩ

Fig 4.2: TEMPERATURE DEPENDENCE OF RESISTIVITY

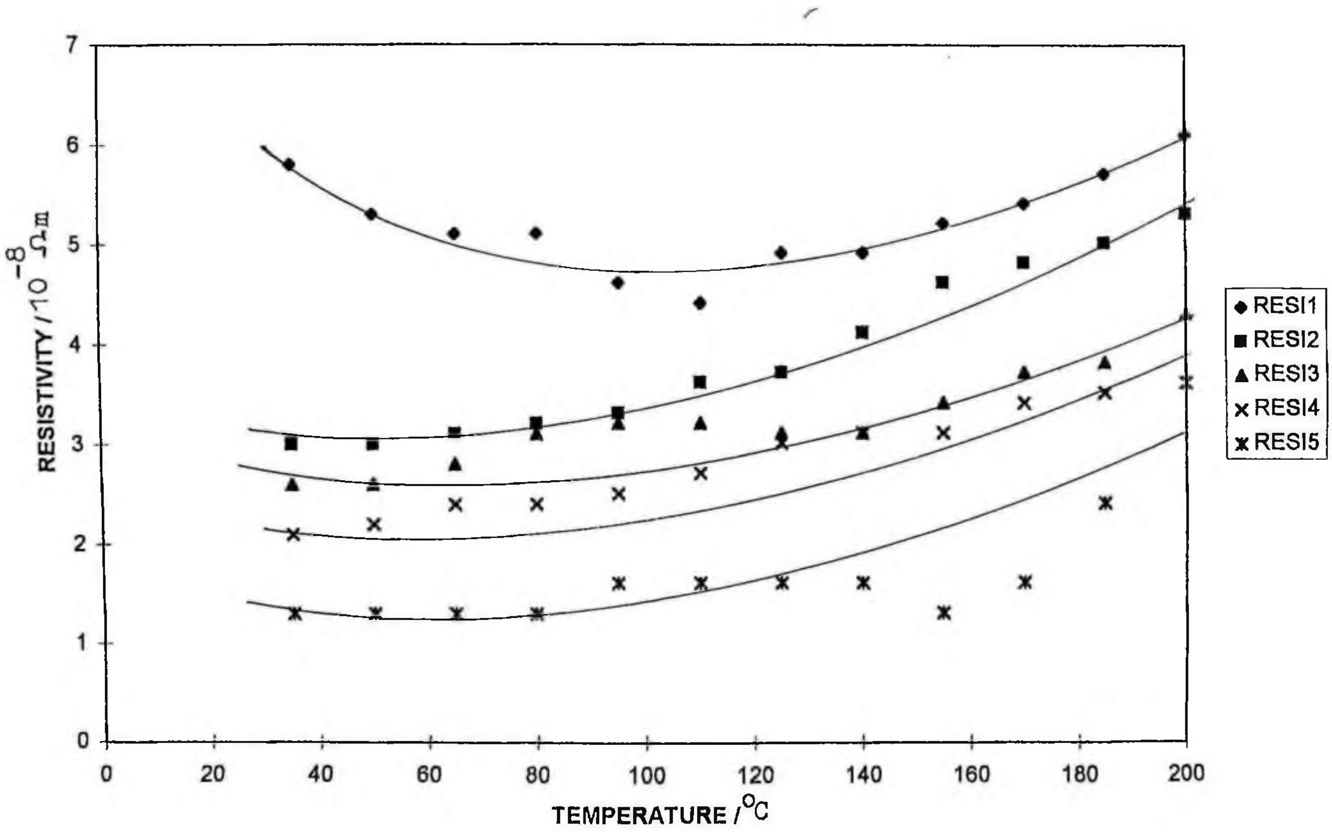


Fig. 4.3: Temperature dependence of resistivity for minalpha of diameter = 0.23mm at different R' 's.

RE1 - $R' = 120\text{k}\Omega$

RE2 - $R' = 395\text{k}\Omega$

RE3 - $R' = 200\text{k}\Omega$

RE4 - $R' = 450\text{k}\Omega$

Fig 4.3: **TEMPERATURE DEPENDENCE OF RESISTIVITY FOR MINALPHA**

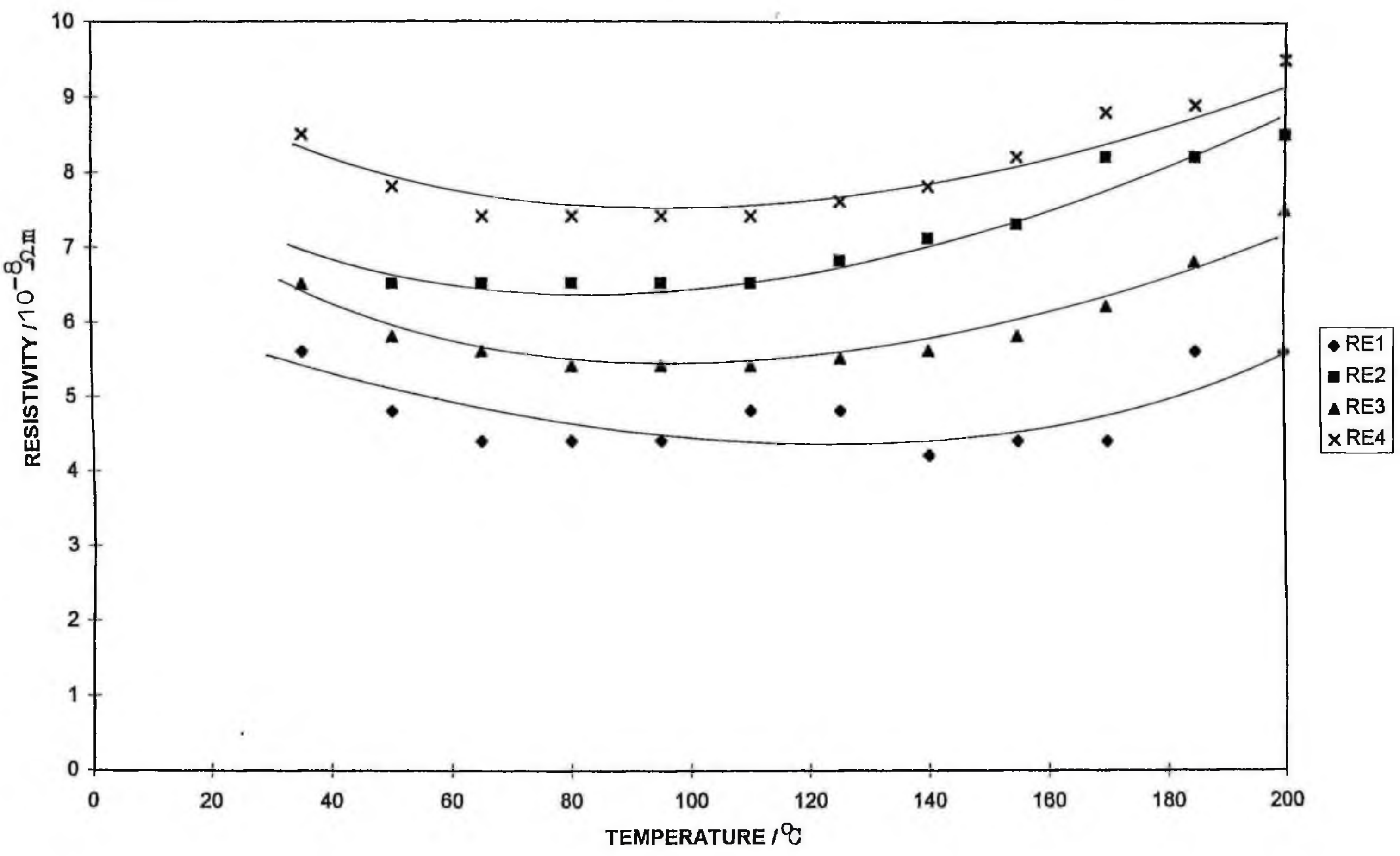
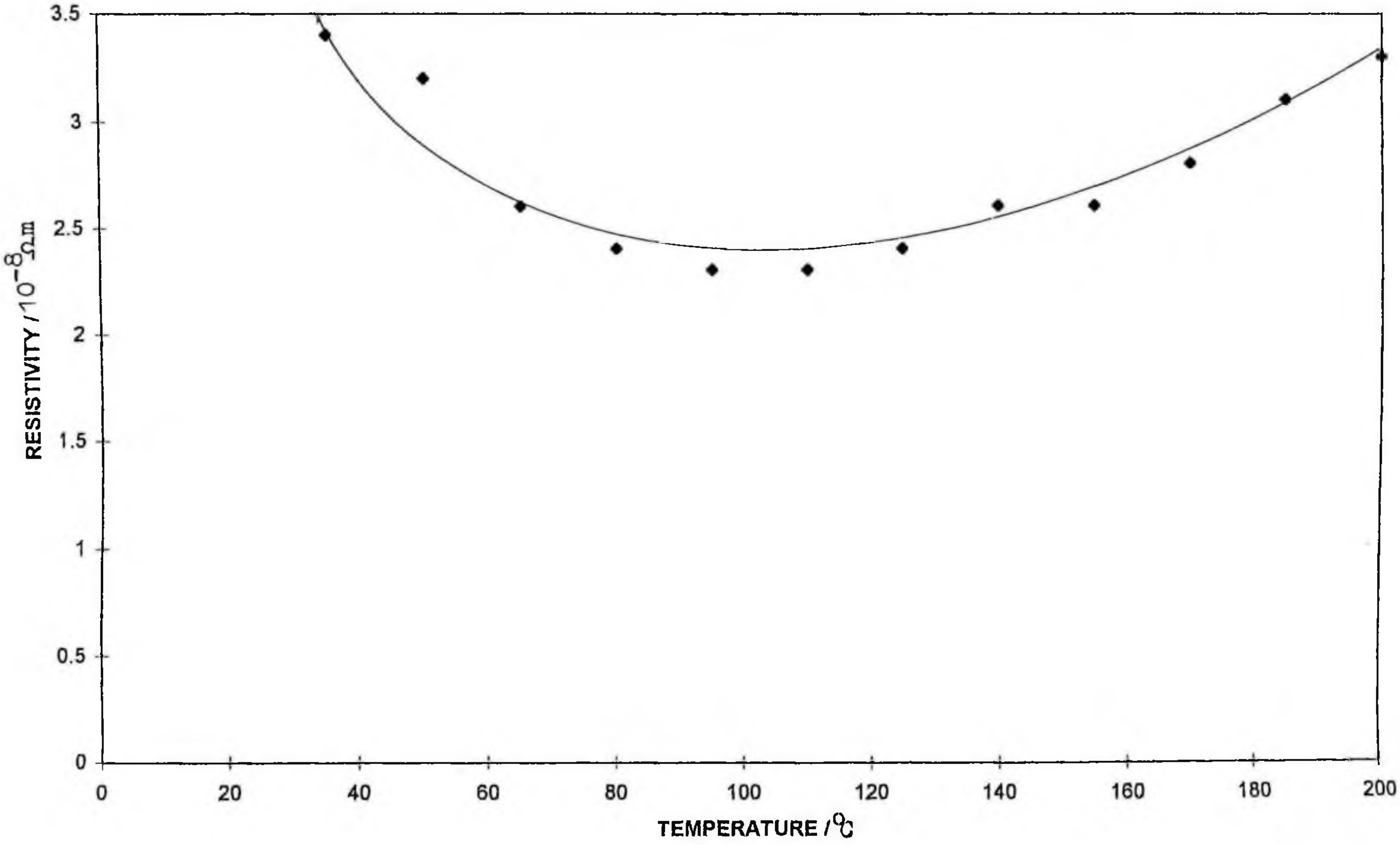


Fig 4.4: **TEMPERATURE DEPENDENCE OF RESISTIVITY FOR MANGANIN**



For manganin of diameter 0.105mm, the curve falls at lower temperatures to a minimum of about 110^{0}C and continues to rise.

Fig. 4.4 shows the temperature dependence of resistivity for minalpha (Cu, Mn, Cl, Al and Na) for various R' 's. There is close resemblance of curves at various R''s. The higher the R' value, the higher the curve which generally rises at lower temperatures, falls and rises again.

The resistivity values for manganin of diameter 0.105mm and R' = 210kΩ are relatively low hence Fig. 4.5 shows the temperature dependence of resistivity for manganin alone. The shape of the graph in this case is similar to those of minalpha (Fig. 4.4).

The results obtained from this section of the work clearly show that the initial rising of the ϱ-T curve at lower temperatures may be due to the fact that at lower temperatures, the initial warming rather causes the lattice and foreign atoms to be more ordered hence the curves fall. However, as the temperature is increased, there is increased thermal activity leading to increased disorder owing to the thermal excitations of the atoms hence the curves rise.

The non-constancy of the temperature would become pronounced at higher temperatures and thereby causing a lot of scatter.

CHAPTER FIVE

CONCLUSIONS

This thesis has considered studies involving (i) the effect of tensile stress on the resistivity of some alloys and metals and (ii) the effect of temperature on the resistivity of these materials. The materials studies are : copper, manganin, tantalum, constantan and minalpha.

In addition to extensive experimental work, there has been appreciation of other works including those of Kuczynski, Rolnick Bridgman and others.

The range of tensile stress applied is of the order of 10^7Pa such that the deformations in the metal and alloys remain elastic. The temperatures employed range between 35^0C and 200^0C.

From the discussions in the previous chapters, the following conclusions can be drawn:

1. The rate of increase of resistivity as stress is applied can be explained in terms of the Young's modulus of the material.
2. Although Kuczynski's work shows that both positive and negative tension coefficients of resistivity are possible, the range of stresses employed in this work is limited to only the positive coefficients.
3. From Fig. 4.1 which illustrates the stress dependence of fractional resistivity for manganin, copper, constantan and tantalum, it is found that in general as the tensile stress increases, the fractional resistivity also increases.

4. As far as the strain coefficients of specific resistivity for constantan are concerned, the percentage composition of Ni in the Cu-Ni alloy (Table 4.3) determines to a large extent the sign or magnitude of these values as $\frac{d\rho}{\rho d\varepsilon}$ becomes negative when the amount of Ni in Cu-Ni alloy increases.

5. From the materials studied, the highest K-value or gauge factor is obtained for tantalum whilst constantan has the lowest. However, all materials studied have K-factors which vary between 2 and 6.

6. On the resistivity-temperature aspect of the this work, it is clearly shown that the initial rising of the ρ-T curve at lower temperatures may be due to the fact that at lower temperatures, the initial warming rather causes the lattice and foreign atoms to be more ordered. However, as the temperature is increased, there is increased thermal activity leading to increased disorder owing to thermal excitations of the atoms.

REFERENCES

Allen, M., Phys. Rev. 42, 848 (1942).

Amuzu, J. K. A., J. Appl. Phys. D : Appl. Phys. 13, L 127-9 (1980).

Amuzu, J. K. A., Measurement of the change in thermoelectric power of Cu and Ag under shear stress., (1986).

Amuzu, J. K. A., The effect of tensile stress on the thermoelectric emf (TEMF) in Cu, Au, and Ag., (1981)

Amuzu, J. K. A., Addoli, P. K., J. Phys. F met Phys., 12, 1637 (1982).

Amuzu, J. K. A., Agyei, E. K., Hodzoade, A., Solid State Commun. 76, 769, (1990).

Amuzu, J. K. A., Toworfe, G. K., Tossou, P. K., Changes in coercivity, remanence and hysteresis power loss in some metallic glasses. (1993).

Baber, W. G., Proc. R. Soc. Lond. A 158, 383, (1937).

Bridgman, P. W., Proc. Am. Acad. Arts Sci. 57, 39 (1922).

Bridgman, P. W., Proc. Am. Acad. Arts Sci. 59, 117 (1923).

Bridgman, P. W., Proc. Am. Acad. Arts Sci. 60, 423 (1925).

Bridgman, P. W., The Physics of High Pressure, Chapters 6 and 9, (1931): London (G. Bell and Sons, Ltd.).

Campbell, D. S. and Hendry, B., Brit J. Appl. Phys. 16, 1719 (1965)

Cochrane, R. W., Strom-Olsen, J. O., Rebouillat, J. P. and Blanchard, A., Solid State Commun. 32, 175 (1979)

Craig, P. P., Goldberg, W. I., Kitchens, I.A. and Budnick, J.I., Phys. Rev. Lett. 19, 1334, (1967).

de Forest, A. V., Instruments 15, 112 (1942).

Donaldson, J. A., Wilson, R. Proc. Roy. Soc. (London) 27, 18 (1907).

Druyvesteyn, M. J., Physica 17, 748 (1951).

Dugdale, J. S. And Gugan, D., Proc. Roy. Soc. A,241, 397 (1957).

Dugdale, J. S. And Gugan, D., Proc. Roy. Soc. A,254, 184 (1960).

Dugdale, J. S. And Gugan, D., Proc. Roy. Soc. A,270, 186 (1983).

Fisher, M. E., Rep. Prog. Phys. 30, 615, (1967).

Fisher, M. E. and Langer, J. S., Phys. Rev. 20, 665, (1968).

Greig, D. and Howson, M. A., Solid State Commun. 42, 729 (1982).

Handler, P., Mapother, D. E. and Rayl, M. Phys. Rev. Lett. 19, 356, (1967).

Kuhl, H., Strain gauges - Theory and Handling, Pillips Electronik Industrie GmbH (1976).

Lederer, P., and Mills, D. L., Phys Rev. 165, 837, (1968).

Linde, J. O., Ann. d. Physik:, 10, 52, (1931); 14, 353, (1932); 15, 219, (1932).

May, A. N., Amuzu, J. K. A., Measurement of the longitudinal piezo-thermoelectric effect in polycristalline wires of the noble metals (1973).

Mills, D. L, and Lederer P., J. Phys. Chem. Solids, 27, 1805, (1966).

Mooij, J. H. and De Jong, M., J. Vacuum ci.Technol. 9, 446 (1972).

Mooij, J. H. et al., Phys. Stat. Sol. (a) 17, 521 (1973).

Mott, N. F., Proc. Camb. Phil. Soc., 32, 281, (1936).

Norbury, A. L., Trans. Farad. Soc., 16, 570, (1921).

Norton, J. T., Kuczynski, G. C., J. Appl. Phys. 19, 683 (1948).

Norton, J. T., Kuczynski, G. C., Instruments 21, 328 (1948).

Perry, C. C. And Lissner, H. R., The Strain Gauge Primer, McGraw-Hill, New York (1955).

Piotrowski, C., Stephen, C. H. and Bass, J., Proc. LT13, Vol. 4, 417, Plenum Press, New York, (1974).

Rolnick, H., Phys. Rev. 36, 506 (1930).

Schindler, A. I., and Rice, M. J., Phys. Rev. 156, 513, (1967).

Smith, N. F., Phys. Rev. 28, 107, 429 (1909).

Tang, S. H., Kitchens, T. H., Cadieu, F. J., and Craig, P. P., Proc. LT13, vol. 4, 385, Plenum Press, New York, (1974).

Thomas, H. Z., Phys. <u>129</u>, 219 (1951).

Thompson, W., Trans. Roy. Soc. (London) <u>146</u>, 649 (1856).

Tomlinson, H., Trans. Roy. Soc. (London) <u>174</u>, 1 (1883).

Volkenstein, N. V., Novoselov, V. A., and Startsev, V. E., Sov. Phys. - JETP, <u>33</u>, 584, (1971).