STRAIN GAUGE TECHNOLOGY

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STRAIN GAUGE TECHNOLOGY

PREFACE

Experimental stress analysis is the strictly practical branch of stress analysis and for most problems it relies heavily on strain measurement techniques. Of these, by far the most widely used is that involving strain gauges in general and electrical resistance strain gauges in particular. These small and basically simple devices have been in use for many years, not only in all branches of engineering, but in almost all industries, and crossing all disciplines. In spite of, or perhaps because of, their enormous field of application, there have been very few published books on the subject. Most of the literature consists of technical papers and reports, referring to specific problems or particular industries.

Strain Gauge Technology, which grew out of Applied Science Publishers' *Developments in Stress Analysis* series, does not replace or supersede existing text books and reference books. The basic theory of strain gauges has not changed, but the performance now available, and the techniques of installation, calibration, and data capture are very different to those used even a few years ago. There have been no revolutionary inventions; what has occurred is a very important steady improvement in materials, and in the techniques of both manufacture and installation, which has made strain gauges far more reliable, accurate, and versatile. They should now be the everyday tools of all engineers concerned with design, prototype testing, or development, as well as for failure analysis.

The performance of precision transducers such as load cells and electronic weighing scales is now very much accepted and even taken for granted. It is often forgotten, or perhaps not known, that the sensors in these devices are usually resistance strain gauges. With commercial scales used in retail shops already offering accuracies of 0·03 % and approaching

0·02 % here is a true indication of the performance and reliability available from resistance strain gauges.

In Part I, Electrical Resistance Strain Gauges, Chalmers discusses present day materials and construction methods for gauges and their performance characteristics. Mordan describes the various adhesives used and the installation methods for a wide variety of applications and performance requirements. This subject is taken further by Pople to cover the particular problems of installation and protection in difficult and hostile environments. Scott and Owens discuss strain gauge instrumentation at length, reviewing the well known and traditional equipment, but adding a powerful introduction to computerised data acquisition and reduction, and to the trends towards high speed digital systems. Part I is concluded with a unique exposition on error analysis which should give every strain gauge practitioner cause for thought.

Part II covers three very important though not so widely used strain gauge groups. Baker introduces and updates the performance characteristics of semiconductor or piezo resistive strain gauges. Procter and Strong review the available capacitance strain gauges, increasingly used for static strain measurement at elevated temperature, and Hornby describes and discusses applications of vibrating wire strain gauges which are particularly well suited to measuring long-term static strains in civil engineering.

This book is intended to fill an important gap between the manufacturers' literature which gives detailed instructions for handling a particular product, and a text book which covers basic theory and general principles of strain measurement. It brings together much needed practical 'know-how' and experience from a number of leading exponents of the various aspects of strain gauge practice. All the authors are practising engineers in the real commercial world, and whilst some are well known for their published work, others have been persuaded for the first time to commit their knowledge and experience to paper. It is hoped that the result will prove equally useful to both 'do-ers' and 'specify-ers.'

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PART I

Electrical Resistance Strain Gauges

CONTENTS

Chapter 1

MATERIALS, CONSTRUCTION, PERFORMANCE AND CHARACTERISTICS

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INTRODUCTION

Since 1940, the bonded electrical resistance strain gauge has been the most powerful single tool in the field of experimental stress analysis. It is one of the most accurate, sensitive, versatile and easy-to-use sensors available. It is relatively low in cost, is linear in output, is easily installed, and is available in a broad variety of configurations, sizes and materials, to meet a very large spectrum of measurement requirements over a wide range of temperatures.

Continuous commercial development, and extensive industrial and research investigations, have resulted in excellent performance characteristics—particularly in stability, temperature compensation, and creep. This, in turn, has led to the strain gauge becoming the basic sensing element of very high precision load transducers and weighing systems, in which there have been rapid developments in recent years (Fig. 1).

In spite of the relative ease with which strain gauges can be employed, the proper and effective use of them requires a thorough understanding of their characteristics and performance, and of the application techniques and associated instrumentation. This chapter is devoted to those features which affect the behaviour of the resistance strain gauge itself. Later chapters deal with adhesives, installation and protection techniques, instrumentation, and errors.

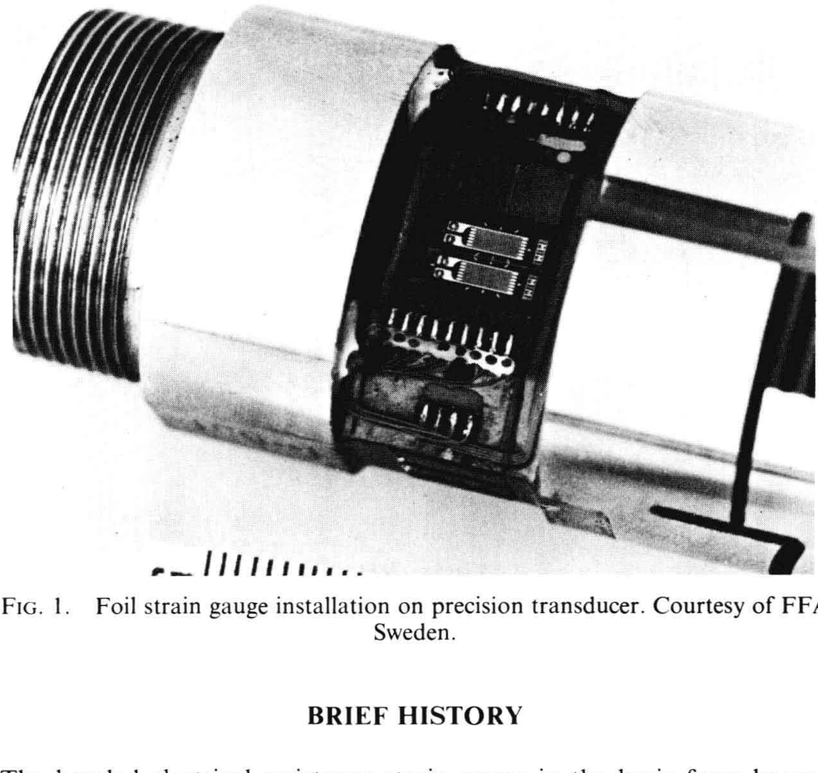

FIG. 1. Foil strain gauge installation on precision transducer. Courtesy of FFA Sweden.

BRIEF HISTORY

The bonded electrical resistance strain gauge in the basic form known today was first used in the USA in 1938. Simmons at the California Institute of Technology, and Ruge at the Massachusetts Institute of Technology, both discovered that small diameter wires made of electrical resistance alloys, such as copper–nickel, could be adhesively bonded to a structure to measure surface strain.

The strain sensitivity of resistance wires was first utilised some years prior to this, however, in the unbonded wire strain gauge. This consisted of an arrangement of wire, wound around a series of pins actuated by linkages, any movement of which stretched the wire and changed its resistance. This was essentially an electrical extensometer, and the principle is still used today in some special types of transducers.

Much earlier still, it was Lord Kelvin who, in 1856, first reported on the relationship between strain and the resistance of wire conductors. He discovered that differences in tension of the wires he was using affected his resistance measurements. This was an inconvenience to him, and he carefully tried to minimise the effect.

It is also important to acknowledge the first use of a bonded resistance strain gauge device in the early 1930s. This consisted of a carbon composition resistor on an insulating strip, used to measure vibratory strains in high performance propeller blades for aircraft. The carbon gauge was, however, limited to the indication of dynamic strains, and could measure these to only a moderate degree of accuracy, owing to the lack of resistance stability with time and temperature.

Following the development of the techniques for bonding resistance wires to structures, discovered by Simmons and Ruge, strain gauge measurements were quickly adopted for structural testing during the rapidly growing aircraft development programmes of World War II. They continued to be used largely in the aircraft industry for a number of years, and it was the requirements of this industry that led to the significantly important development of the foil type of strain gauge in 1952. The Saunders–Roe Company in the UK was seeking improvements in the bonded wire gauges, which were presenting problems in harsh testing environments on helicopters and flying boats. At that time, printed circuit techniques were appearing, and Saunders–Roe developed the idea of making a strain gauge by etching the grid from a thin foil of the appropriate resistance material. This foil strain gauge was found to have a number of distinct advantages, and was rapidly adopted, particularly by manufacturers and users in the USA. It opened the way for much more extensive industrial use of strain gauge techniques, and today it is by far the most widely used type of gauge worldwide.

Variations of the foil strain gauge are produced by die cutting, as opposed to etching, and by vacuum deposition techniques for particular purposes discussed later. The majority of development effort since the introduction of the foil gauge has, however, been toward improved control and understanding of gauge materials, characteristics and design.

BASIC OPERATING PRINCIPLE

All electrically conductive materials possess a strain sensitivity—defined as the ratio of relative electrical resistance change of the conductor to the relative change in its length—and therefore could be considered as possible strain gauge materials. The strain sensitivity is a function of the dimensional changes which take place when the conductor is stretched elastically (which will be essentially the same for different materials), plus any change in the basic resistivity of the material with strain.

The electrical resistance of a conductor is given by

$$R = \rho l / A \quad (1)$$

where R = resistance, l = length, A = cross-sectional area and ρ = resistivity.

Strain sensitivity (which, for a strain gauge, is defined as *gauge factor*) is a dimensionless relationship expressed mathematically as

$$F = \Delta R / R / \Delta l / l \quad (2)$$

where F = strain sensitivity, R = initial resistance, ΔR = change in resistance, l = initial length and Δl = change in length.

From these two formulae, the basic strain sensitivity can be established due to the dimensional changes, assuming that the resistivity (ρ) remains constant. If the conductor is stretched elastically, for a given change in length (Δl) there will be an associated reduction in cross-sectional area due to the Poisson effect. These two effects are additive in increasing the resistance of the conductor, and assuming a Poisson's ratio of 0·3 (which is approximately the same for most resistance materials) the sensitivity factor is about 1·6, i.e. $F = 1 + 2v$.

In fact, however, tests on various resistance materials have shown that they exhibit widely different values of strain sensitivity (Table 1). These

TABLE 1
STRAIN SENSITIVITY OF VARIOUS MATERIALS

Material	*Trade name*	*Typical strain sensitivity*
Copper–nickel (55–45)	Constantan Advance	+2·1
Nickel–chromium (80–20)	Nichrome V	+2·2
Nickel–chromium (75–20) plus iron and aluminium	Karma	+2·1
Iron–chromium–aluminium (70–20–10)	Armour D	+2·2
Nickel–chromium–iron–molybdenum (36–8–55·5–0·5)	Isoelastic	+3·5
Platinum–tungsten (92–8)	—	+4·0
Copper–nickel–manganese (84–4–12)	Manganin	+0·6
Nickel	—	−12·0
Iron	—	+4·0

variations indicate that the specific resistivity (ρ) of the materials must be affected by strain, or perhaps more directly by the associated internal stress in the material. Strain sensitivity is, therefore, a combination of the effects of geometric changes plus a resistivity change due to changing internal stresses.

Beyond the elastic limit of the material, however, the change in internal stress approaches zero, and Poisson's ratio (ν) approaches 0·5. In this case, resistance changes due to strain are primarily due to dimensional changes and the strain sensitivity ($F = 1 + 2\nu$) approaches 2·0.

This means that materials which have a strain sensitivity appreciably different from 2·0 in the elastic range will have values approaching 2·0 in the plastic range, with the associated non-linearity which this variation implies. It would appear from this, therefore, that only those alloys which have a sensitivity of approximately 2·0 in the elastic range will remain essentially linear over a wide strain range, and this is generally true of the most commonly used strain gauge materials. Some materials which have an attractively high sensitivity in the elastic range are in fact highly non-linear, which means that the sensitivity varies with strain, rendering them undesirable for strain gauge purposes.

MATERIALS

The basic materials used in the manufacture of the resistance strain gauge are those of the grid (the strain sensitive resistance element) and the backing, which will be considered separately.

The Strain Sensitive Resistance Element

Some of the desirable features for a strain sensitive resistance element are:

(1) Linear strain sensitivity in the elastic range—for accuracy and repeatability.
(2) High resistivity—for smallest size.
(3) Low hysteresis—for repeatability and accuracy.
(4) High strain sensitivity—for maximum electrical output for a given strain.
(5) Low and controllable temperature coefficient of resistance—for good temperature compensation.
(6) Wide operating temperature range—for the widest range of applications.
(7) Good fatigue life—for dynamic measurements.

Table 1 summarises the strain sensitivity of a number of resistance materials which might be considered for strain gauge purposes. In practice, only a few alloys come close to meeting the most desirable features; and the main ones, with a summary of their characteristics, are as follows.

Copper–Nickel Alloy

The strain gauge alloy is generally referred to as constantan, although this name also applies to a slightly different composition, used for thermocouples. Other trade names include Advance, Cupron and Copel.

Of all modern strain gauge alloys, copper–nickel (55–45) is the oldest and still the most widely used. This reflects the fact that it has the best overall combination of properties needed for many strain gauge applications. This alloy has, for example, an adequately high strain sensitivity which is relatively independent of strain level and temperature. Its resistivity is high enough to achieve suitable resistance values in small grids, and its temperature coefficient of resistance is not excessive. In addition, it is characterised by a moderate fatigue life and a relatively high elongation capability. Very importantly, it can be self-temperature compensated to match a wide range of test material expansion coefficients.

Operating temperature range is generally between $-50\,°C$ and $+150\,°C$, but the alloy may exhibit continuous small changes in resistance with time, at temperatures in excess of $+70\,°C$. At higher temperatures it becomes progressively subject to oxidation, leading to significant resistance changes with time.

The strain range of copper–nickel in its standard form is up to $\pm 5\,\%$ and up to $20\,\%$ in a super-annealed form.

Nickel–Chrome Alloys

The nickel–chrome alloys are the next in popularity as strain gauge materials. Modified Karma or K-Alloy, which is a 75–20 nickel–chrome alloy with additions of iron and aluminium, is one of the most important of the strain gauge alloys. It has good fatigue life, significantly better than copper–nickel, excellent stability, and its overall performance characteristics are superior to any other alloy currently available.

Its temperature coefficient of resistance can be adjusted by heat treatment to provide temperature compensation on various materials over a wide strain range. Its strain sensitivity, which decreases with temperature, can be controlled within limits to compensate for the reduction in modulus of elasticity with temperature of materials used for precision transducer applications.