1 Historical review

It is an irrefutable fact that the strain gage was invented by two different people at almost the same time. They were situated at widely separated places in the USA and they did not, at that time, have any contact with each another [1.1]. Professor Arthur C. Ruge of the Massachusetts Institute of Technology (MIT) was one of these inventors; the other was Edward E. Simmons. At the California Institute of Technology (Caltech) in 1936, Simmons was investigating the stress–strain behaviour of metals under shock loads. He was at the time a student and worked as a research assistant at the Institute.

To measure the force introduced in the specimens by impact, he used a dynamometer equipped with fine resistance wires made from constantan. The tests carried out by Simmons were part of a research project of Dätwyler and Clark that started in 1936 [1.2]. Although details of the tests and the measurement method used were not published until 1938 [1.3], the start date of the project (1936) shows that it was Simmons who invented the strain gage principle. Publication about the tests and the used measurement method was divulged not before 1938 [1.3]. In 1940, Simmons's invention was patented at the United States Patent Office. Figure 1.1 shows the test equipment that Simmons used for the measurement of shock loads on metal specimens. The dynamometer is equipped with measuring wires made from constantan. The drawing is taken from the Patent [1.4]. This shows that a strain gage based transducer was patented before the strain gage itself.

In 1938 the other inventor, Professor Arthur C. Ruge, with the support of his assistant J. Hanns Maier investigated in the field of engineering seismology the influence of earthquakes on mechanical structures. His test object was a small scale model of an elevated water tank, mounted on a vibration table. However, because the stress was low and the model's skin extremely thin they failed to measure the strain in the tank wall using normal mechanical or optical strain instrumentation available at that time. One day the saving idea came to him, and he attached the thin wire from a potentiometer with Duo household cement to the water tank and was immediately rewarded with excellent and reproducible measurement values.

The resistance change in metallic wires caused by strain due to tensile loading changed the voltage drop in the wire and could be measured with a simple bridge circuit [1.5, 1.6]. The strain gage was now born also on the east coast of the USA.

Figure 1.2 shows a photograph taken by J. Hanns Maier of Professor Ruge carrying out experiments on the model of a water tank using the first strain gages invented by him and his assistant Maier. Strain gage rosettes are cemented to the model's base. Also visible in the photograph is an acceleration transducer made by Ruge using resistance wires.

For easier handling Ruge cemented the measuring wire to a carrier paper that had been stiffened by cementing the paper to two Plexiglas end pieces with a brass spacer bar serving as a handling frame and lead wire holder. The brass spacer bar was

Technology and Practical Use of Strain Gages: With Particular Consideration of Stress Analysis Using Strain Gages. First Edition. Stefan Keil.

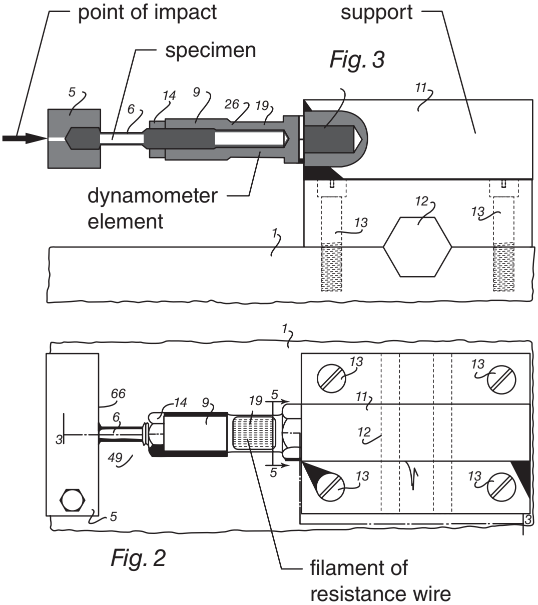


Fig. 1.1 E.E. Simmons's dynamometer equipped with measuring wires for the measuring of shock loads on metal specimens [1.4]

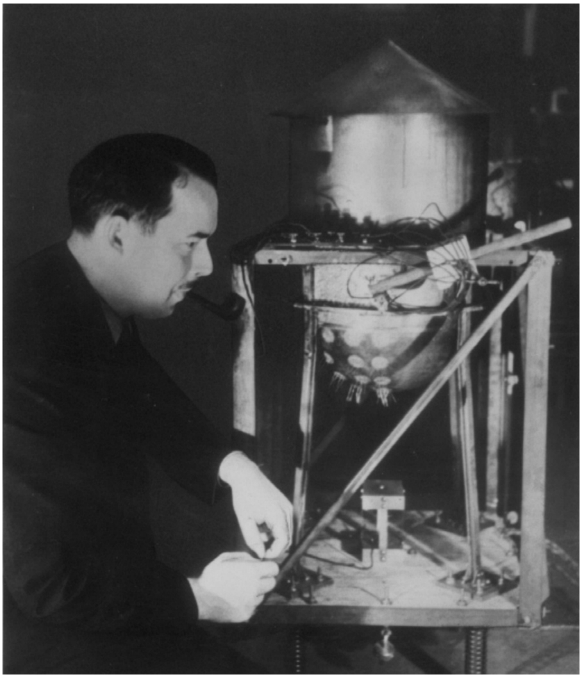
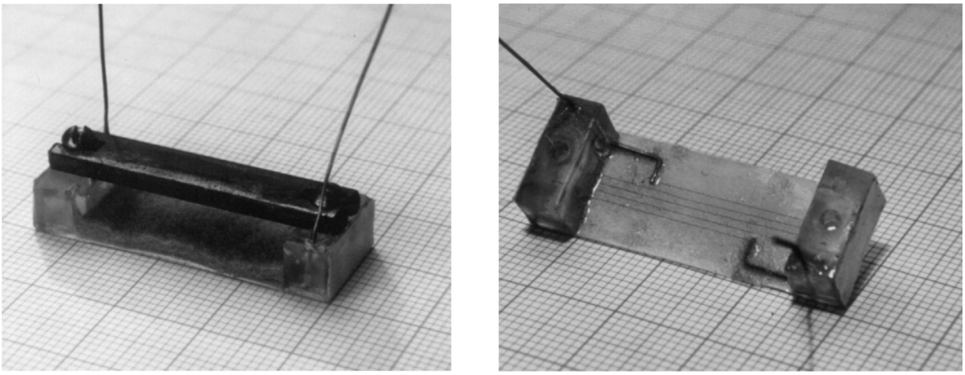


Fig. 1.2 A.C. Ruge carrying out experiments on a small scale model of a water tank fitted with the first strain gages mounted on a vibration table in 1938



a) b)

Fig. 1.3 Ruge's strain gage from 1938 a) with brass bar as an installation aid b) without brass bar and without grid protection layer

removed after cementing. Figure 1.3 shows one of the first strain gages made by Ruge with and without brass bar and with the felt protection layer removed. The strain gage seen in Figure 1.3 was patented in 1944 [1.7].

In 1938 in accordance with custom, Ruge duly submitted the bonded wire 'resistant strain gage' idea to the MIT patent committee. The committee's answer deserves quoting. The reply of the MIT reads: ' . . . *this development is interesting; the Committee does not feel that the commercial use is likely to be of major importance...any rights which the Institute may have in this invention should be waived in your favour* . . . ' [1.8]. This meant that Ruge was free to exploit the invention as his own.

In 1939, Ruge and his colleague Professor Alfred V. deForest, with support of the heavy machine construction firm Baldwin-Southwark Corp. started the manufacture and sale of strain gages. The first answer by Baldwin-Southwark to Ruge's licence offer is also worthy of note: '*We are in the locomotive business and not going to make postage stamps*' [1.6]. But after a convincing demonstration of strain gage performance in 1939, a profitable cooperation started between Ruge-deForest and Baldwin-Southwark. The beginning was marked by the registration of the strain gage. The invention was patented by the United States Patent Office on June 6 in 1944. When, in 1955, Ruge-deForest sold out to Baldwin-Lima-Hamilton, at that stage they employed more than 200 people.

Before the patent registration of Ruge's invention, Baldwin-Southwark arranged an agreement between Simmons and Ruge-deForest that recognized Simmons as well as Ruge as inventor of the strain gage [1.6]. At the end of the discussion which led to the agreement, Tatnall suggested in a spirit of fun that the new product be named SR-4; S and R for Simmons and Ruge, and the numeral 4 representing the four people who took part in the final discussion (Tatnall as instigator of the discussion, Clark as colleague of Simmons from Caltech, deForest as Ruge's colleague from MIT and

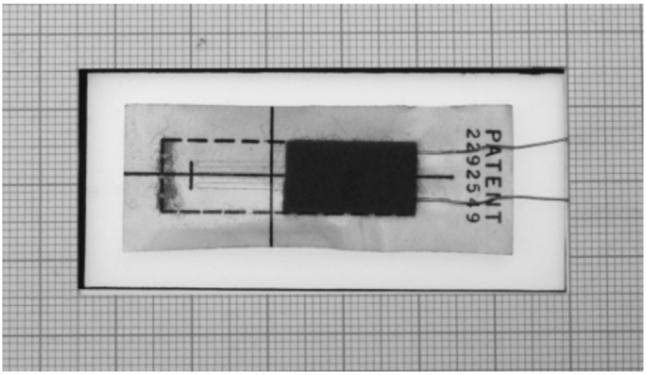


Fig. 1.4 SR-4 strain gage with paper carrier from 1941 the protective felt layer is half removed

Hathaway as patent attorney from Baldwin). This designation was registered as a trademark.

Figure 1.4 shows an SR-4 strain gage with paper carrier as it was when it became world-famous. It can be seen from Figure 1.4 that the SR-4 strain gage bears the number 2 292 549 of Simmon's patent. After the SR-4 agreement a legal battle ensued between Simmons and Caltech for whom Simmons was working when he made the invention. Caltech claimed they sponsored the development and asked a 60/40 split on royalties. Caltech lost the case, because, at the time the invention was made, Simmons was a student and not on the Caltech payroll.

In 1939, Ruge and deForest started their partnership with Baldwin-Southwark for development engineering and manufacture of strain gages and strain gage devices for sale. In 1941, they got the first solid sizeable order from Baldwin for stock gages – 50 000 in one order for all types. These were intended to last a year, but actually lasted two month. Figure 1.5 shows one of the first strain gage packages as sold in that time.

Simmons and Ruge were not the first scientists to recognize the resistance change in metallic wires caused by tensile loading and the possibility of using this phenomenon to measure mechanical quantities [1.9].

In 1908, the privy councillor Dr S. Lindeck was working on the development of precision resistors at the National Technical Institute (Physikalisch-Technische Reichsanstalt) in Berlin. He wound thin Manganin wire, embedded in shellac, onto brass tube coil formers. He was amazed when he found that the resistance of these elements was dependent on the weather. He found that rising humidity caused the shellac to swell, straining the manganese wire, whose resistance increased.

To investigate this phenomenon in more detail, he closed off both ends of the tube wound with the Manganin wire and placed it under an internal pressure of about 60 bar. As a result, the resistance changed proportionally with the pressure – and therefore with the strain – and suggested that this effect could be used in pressure measurement [1.10]. Unfortunately no-one at that time took up Lindeck's idea which only received its technical verification in a patent from Simmons for a bonded strain

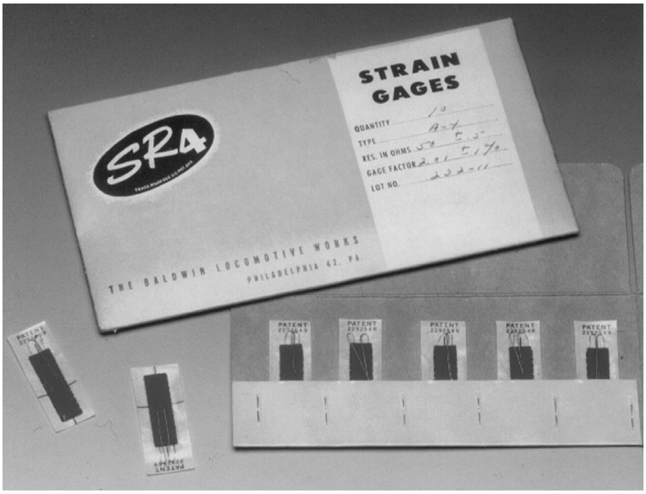


Fig. 1.5 One of the first strain gage packages as sold by Baldwin in 1941

gage pressure transducer about 35 years later [1.11]. Because no figure of Lindeck's equipment is available, a sketch from Simmon's patent is all we can give here, in order to explain Lindeck's suggestion. Figure 1.6 gives the sketch from this patent.

The first technical application of the change in resistance of wires in dependence on their strain for the measurement of pressure was made by Nernst [1.12]. The photograph in Figure 1.7a, which was first published in 1928, shows the pressure indicator designed by Nernst. He used freely tensioned resistance wires of 0.5–1.0 mm diameter and a few centimetres in length which were strained in proportion to pressure. The cylindrical transducer body contains a piston which is pushed by the pressure against the tensioned wires.

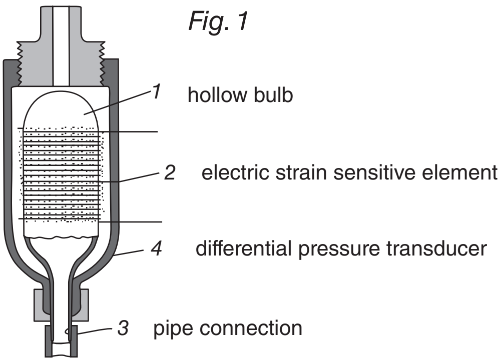


Fig. 1.6 'Bonded strain gage pressure transducer', resistance wire wound on a thin-walled tube with closed ends [1.11]

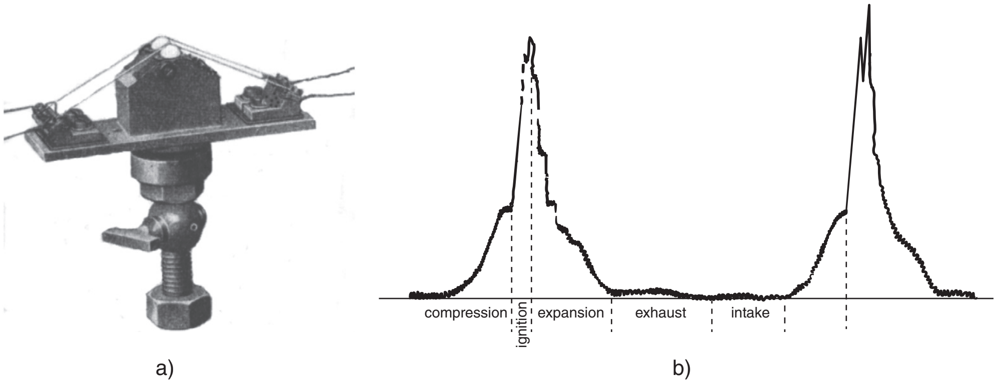


Fig. 1.7 First technical application of the change of resistance due to strain for pressure measurement a) pressure transducer developed by Nernst in 1917 b) pressure curve in an internal combustion engine measured with the transducer shown in a)

The Figure 1.7b shows the pressure characteristic in the cylinder of a combustion engine as measured by Nernst with this device. With the aid of this pressure transducer Nernst could measure the point of ignition in a four-stroke engine. The change in resistance is very small, but it is sufficient to feed an oscilloscope. This pressure transducer was first used by Nernst in 1917, who was at that time with Siemens and Halske in Berlin [1.13].

Another device, which was used in civil engineering for strain measurements in concrete and which had freely tensioned resistance wires, was described by Eaton in 1931 under the designation 'electric resistance strain gage' [1.14]. The device, shown schematically in Figure 1.8 [1.15], contains a Wheatstone half bridge circuit consisting of prestressed wire sections. One bridge arm has two sections which are strained

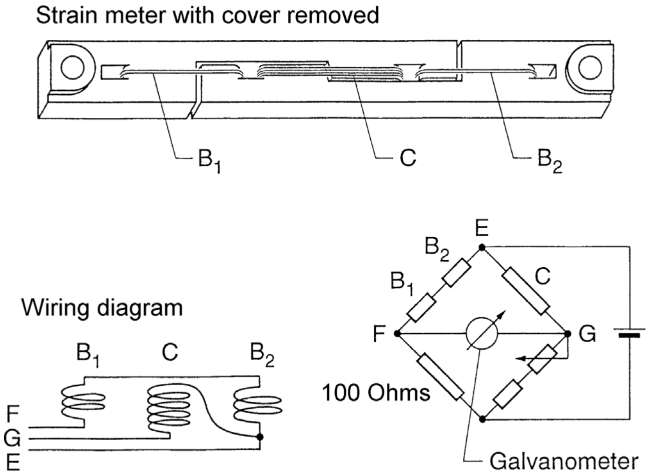


Fig. 1.8 Schematic sketch of the 'electrical resistance strain gage' made by Carlson in1931 which had freely tensioned resistance wires for strain measurement in concrete [1.15]

when the device is pulled, whereas another section in the other arm of the bridge is relieved.

In 1935, Carlson, upon whose idea the design is probably based, reported that about 1500 of these strain measuring devices in an encapsulated version were cast in concrete constructional elements. However, he also reported on the numerous problems that occurred during measurements, such as through temperature effects and corrosion [1.16].

All the historical examples described above are based on the change in resistance of wires stressed by mechanical strain. In all cases, a Wheatstone bridge circuit was used to measure the change in resistance. This bridge circuit was invented by two scientists in the UK, who independently of one another, were dealing with electrical circuits to measure the electrical resistance of metallic wires. Their names were Samuel Hunter-Christie and Charles Wheatstone. They used the knowledge gained by Simon Ohm [1.17] to develop a circuit, with which it was possible to measure the electrical resistance of wires in spite of the instability of the voltage sources that were then available. Although Hunter-Christie published information about his circuit in 1833 [1.18], and it was ten years before Wheatstone's publication in 1843, the circuit was called after Wheatstone. This circuit became the standard circuit for measurements using strain gages and is still widely used today.

Figure 1.9 shows the Wheatstone bridge circuit in its original form. This circuit enabled Wheatstone to measure the resistance of electrical connecting wires in spite of the instability of his voltage source. He wrote about the response of his galvanometer to changes in the strain of the copper wire that was used [1.19], and the date of these measurements (1843) was very early in the history of strain gages.

In Figure 1.9 we can see the historic measurement device as used by Wheatstone in 1843. It consists of a wooden board with screw clamps Z and C used for connecting the supply voltage, the resistance wires Za and Ca, and screw clamps c, d, e and f for connection the resistances to be measured. Wheatstone tapped the diagonal voltage between a and b, using a sensitive galvanometer. An adjustable short-circuiting arm mn served as a zero balance.

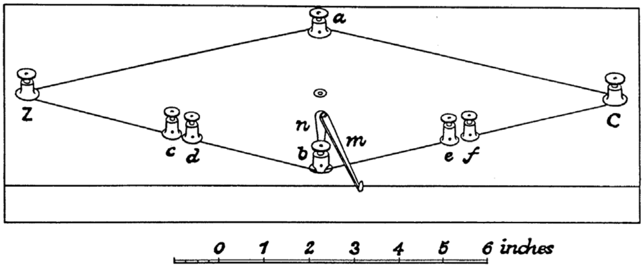


Fig. 1.9 The Wheatstone Bridge Circuit in its original form (1843) [1.19]

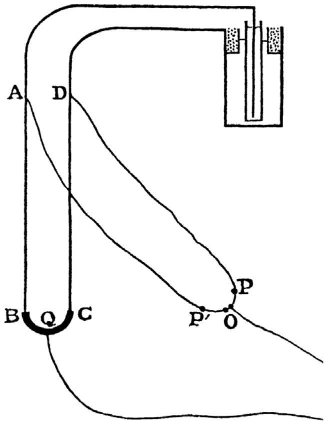


Fig. 1.10 Thomson's bridge circuit for the measurement of changes in the resistance of metal wires under tensile load (1856) [1.20]

Wheatstone explicitly made reference to his circuit's suitability for the measurement of small changes in resistance, and even at this early stage he was able to perceive relative changes in resistance of about two parts per thousand.

The next step was made by Thomson. Also in England, he conducted the first objective investigations into the changes of resistance caused by the strain in wires in 1856. He used a bridge circuit as invented by Wheatstone, in which, as shown in Figure 1.10, thin copper or iron wires were stretched by weights [1.20]. He found proportionality between the strain and the change of resistance and determined several gage factors, as they would be called today, but without specification of exact data.

Thomson used in his test device the bridge circuit as invented by Wheatstone, but without any knowledge of Wheatstone's invention. In this way the Wheatstone bridge circuit was invented again.

Both Wheatstone's and Thomson's paper had long footnotes about their appropriate priorities. For example, Thomson wrote that he found out one hour before his lecture that Wheatstone had already discovered a similar circuit. In those days, it was more a matter of personal honour to be the first with the invention than to protect the invention itself by means of a profitable industrial patent.

The first systematic investigation into resistance change of various wires during tensile loading took place in the 1930s. E. Cerlinsky, working at the German Research Institute for Aviation in Berlin-Adlershof, found that constantan wire was the most suitable material for measurement purposes, a fact which still applies today [1.21].

Figure 1.11 illustrates the research setup used by Cerlinsky. A 30 cm long measuring wire as part of a Wheatstone bridge circuit was strung between a fixed point and the

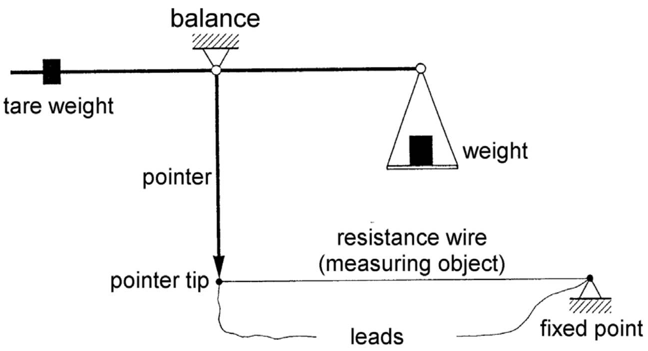


Fig. 1.11 Research setup for measuring the gage factors of resistant wires as performed by Cerlinsky in 1938

tip of the pointer on a balance. The balance was loaded using a weight and tared using a counterweight. The modulus of elasticity of the wire material could also be determined by measuring the displacement of the tip of the pointer with a microscope.

After the invention of the strain gage in 1938 in the USA it was quickly recognized that one could measure more than just strain with strain gages. All mechanical quantities that cause strains in materials can then be detected indirectly by using strain gages. The first transducers equipped with strain gages were built. The major benefits of the new measurement principle led to the improvement of strain gages through systematic development work. They became smaller and less sensitive to temperature, creep behaviour, and fatigue strength was improved. With strain gages used for the construction of transducers the more favourable, less moisture-sensitive phenolic resin (Bakelite) was used as the carrier material.

Initially with strain gages mainly were built transducers for pressure and torque. Strain gages offered in the 1940s the only way to measure power in drive trains of engines under operating conditions without affecting their dynamic characteristics through effects on the measured object. Force transducers with strain gages firstly were used in 1938 at the MIT in wind tunnel measurements on model aircrafts [1.22]. The simple way by installing strain gages on a construction part making this to a force measuring element quickly became known and used. These measuring elements brought no additional measuring displacement into the system and did not change its stiffness. The new method did not need any moving parts such as levers or pointers. With appropriate cover of the measuring points quantities could be measured even under harsh environmental conditions. Probably the biggest advantage was in the electrical output signal that could be transmitted over long distances to a measuring station. One of the first spectacular applications was the centre of gravity determination of aircraft during the loading process with the help of strain gages installed on the landing gear. In 1942 this possibility was used by Cox and Stevens Aircraft Company with force transducers developed by Ruge-DeForest [1.22, 1.23].

In 1952, a further important step of strain gage development was taken by Peter Jackson in the UK, when he invented the etched foil strain gage [1.24–1.26]. He was working at Saunders-Roe on the Isle of Wight and was occupied with stress analysis of rotors of helicopters. He had difficulties with the then available wire strain gages because of fatigue failures, slip ring noise problems and lack of sensitivity. He had problems getting undisturbed signal transmission from the rotating parts, and with the poor dynamic strength of the wire strain gages which were then being used. Signal transmission from the rotating part using slip rings required high output signals because the big slip rings with their high rim speed generated high noise voltage. During his daily crossing by ferry from Southampton to Cowes, Jackson learned from talks with colleagues about circuits made by etching copper-clad Bakelite, which were being used in amplifiers. These first printed circuits were developed by Paul Eisler who was at that time working with the Technograph Company [1.27].

As a result the idea arose to try to make strain gages also by etching foils similar to the printed circuits with the aim of producing strain gages that could withstand higher supply voltages than wire gages. This idea was realized with the aid of the Technograph Company who had produced the first printed circuits in cooperation with P. Eisler. It was thought at the time that these new strain gages with a cost of only a few cents each would force the wire gage off the market. However, the first foil gages had large dimensions and poor fatigue characteristics due to the rough etched edges. It took a few years before foil strain gages reached a satisfactory quality. Figure 1.12 shows foil strain gages from the early Saunders-Roe production. Due to the fact that there are certain limits for the supply voltage of wire strain gages Jackson initiated the

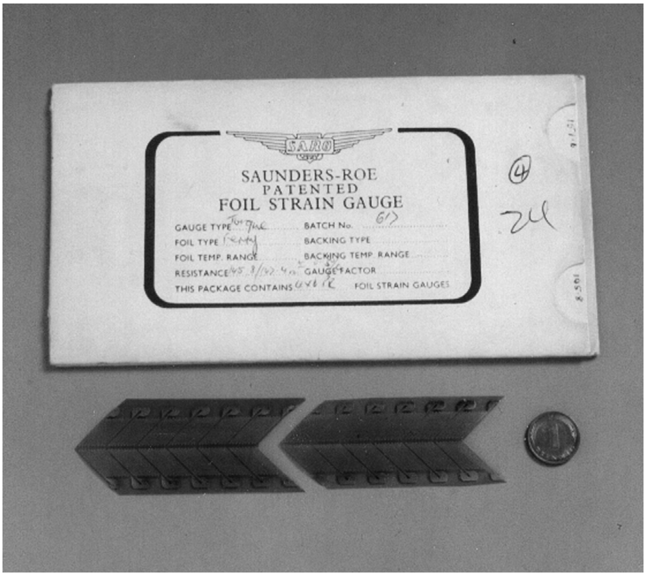


Fig. 1.12 First foil strain gages produced by Saunders-Roe

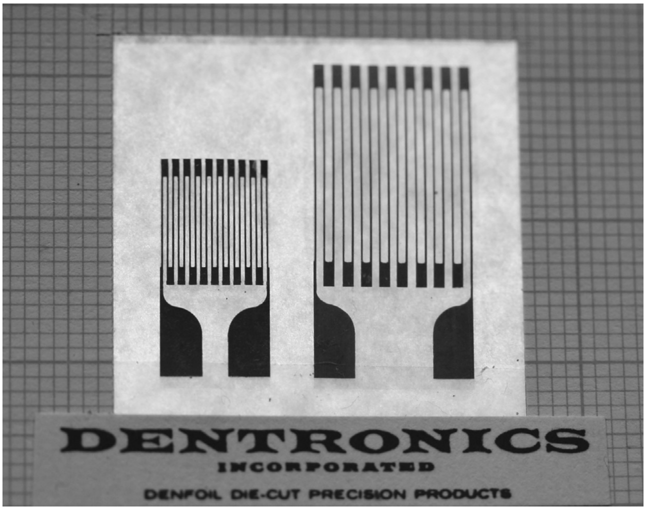


Fig. 1.13 Die-cut strain gages manufactured by Dentronics Inc. in the 1960s

production of foil strain gages and used them for his task. The first foil strain gages made by Saunders-Roe were made from CuNi foil with 0.02 mm thickness and nominal resistance of 55 Ω.

Technograph produced the first foil strain gages for Saunders-Roe and Tinsley under a Saunders-Roe licence. Jackson did not show interest in applying for a patent for which Technograph had applied in the US. The story is given in more detail in [1.28]. There one can read that Peter Jackson attended the 1988 Fifty-Year Anniversary Celebrations of the strain gage in Portland, Oregon, where he was horrified and speechless that his invention was attributed to Paul Eisler, who was instrumental in commercializing Peter's invention, an application of the printed circuit, made by Technograph. Since Peter Jackson had left the UK in 1955, he did not even know about that part of strain gage history and how popular and widespread his invention had become [1.28]. In 2000, Peter Scott Jackson passed away at the age of 84 in Del Mar, California.

A different method of foil gage production was developed by Denyssen in the USA. In 1963, a US patent was granted to Pete Denyssen of Dentronics Inc. concerning the manufacturing of foil strain gages by using a die-cut method, by contrast to the more common chemical etching process [1.29]. Figure 1.13 shows strain gages produced by using the die-cut method.

The main advantages of die-cut strain gages were that foil material could be used that could not be chemically etched by eliminating the etched 'feather edges' the fatigue life could be improved. Dentronics' biggest customer for these gages was Lockheed. Dynisco also used Dentronics' platinum–tungsten strain gages with strain sensitivity

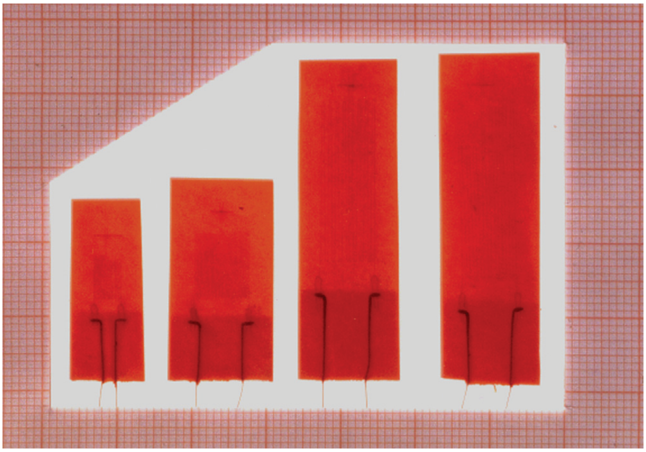


Fig. 1.14 First strain gages manufactured by Hottinger Messtechnik GmbH in Darmstadt; they were flat-grid Bakelite gages

over twice that of the conventional constantan foil, which worked at lower stress levels and hence had higher overload capability.

In 1972 Dentronics Inc. was taken over by the Magnetic Head Company, and ten years later Magnetic Head Company ceased its production, and since then die-cut strain gages have been only of historic interest [1.30]. A remark should be made here about the invention by Denyssen: in 1948 in the USA a patent was granted to van Dyke and Dennis about manufacturing strain gages by punching [1.31].

The first strain gages to be produced in large quantities in Germany were manufactured by the former Hottinger Messtechnik GmbH. In the wake of a licence contract with Baldwin-Lima-Hamilton Corp. (USA), Karl Hottinger gained access to the expertise of the BLH Corporation with regard to the manufacture of strain gages and strain gage transducers [1.32]. In June 1955, Hottinger began preparations for his own production of strain gages in Germany. In December 1955 the first pilot production batch of German manufactured strain gages was offered.

Figure 1.14 shows samples from the first production batch, which were offered under the designation FB (F = flat grid; B = Bakelite). Hottinger started his strain gage production with the intention of using them as the basis for the production of transducers. In 1956, Hottinger Messtechnik GmbH began selling its first load cells, which were fitted with Hottinger Messtechnik strain gages.

The design of the spring element for his transducer (Figure 1.15) has, despite the lack of experience in those days, stood the test of time, and it is still used with only slight modifications today [1.33].

Another essential step for mass production of sensor and transducer elements was taken with the introduction of the lamination technique. The production technology

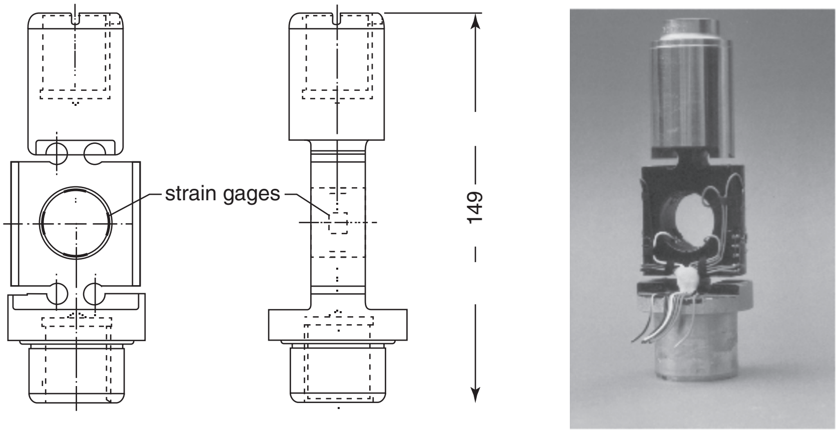


Fig. 1.15 Spring body of the first load cell made by Hottinger Messtechnik GmbH in 1956 [1.32] (nominal load ±2 t, accuracy class 0.2%)

of foil strain gages is based on photo-chemical etching. Using this method any shape of flat grid patterns can be translated into a greatly reduced real measurement grid. The method not only allows the etching of single strain gages from the foil, but in one operation you can etch complete full- or half-bridge circuits, including connecting elements and more or less complicated balancing and compensating structures [1.34]. Such a full bridge circuit being on a carrier foil can be laminated in a single operation on the spring body of a transducer [1.35]. The time-consuming gluing of individual strain gages and their interconnections with soldered wires is thus replaced by the lamination technique with a single production step.

Another possibility for installing strain gage circuits on measuring bodies of transducers is provided by the thin film technology that was introduced in the early 1970s. This technique involves successively depositing on the measuring body an insulating layer, a highly conductive contact and reverse zones, the metal resistor patterns and finally an inorganic insulating layer [1.36].

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