Noble Metal Alloys as Strain Gauge Materials

THEIR DEVELOPMENT FOR HIGH TEMPERATURE APPLICATIONS

By Lizhen Tong and Jinxing Guo
Institute of Precious Metals, Kunming, Yunnan, P. R. China

The development of materials which contain the noble metals for use in high temperature strain gauges is reviewed, with particular emphasis being placed upon work done by the Institute of Precious Metals, in China. Three alloy systems displaying excellent resistance to oxidation and good overall properties when used in high temperature strain gauges, are singled out for examination. These are platinum-tungsten-rhenium-nickel-chromium-yttrium, gold-palladium-chromium-platinum-iron-aluminium-yttrium and palladium-chromium. Their development and the suitability of these alloys for use in measuring high temperature static strain are discussed.

Experimental stress analysis is an indispensable research technique in scientific work, and the theory and practice of stress analysis has undergone great development from the time when the first thin wire resistance strain gauges were made. With the advance of science and technology, there are more and more stringent requirements for precision and sensitivity in automatic control systems and for the measurement of various non-electrical parameters. This has resulted in a wide utilisation of strain gauge materials. Many kinds of sensors have been developed to convert such non-electrical parameters as temperature, pressure, velocity and acceleration, into electrical ones, by using resistance strain wires, so that they can be measured and controlled.

The hot-stresses which are found in the structures exposed to high temperatures in aerospace and nuclear engineering, for example in parts of space vehicles and hypersonic aircraft engines, need to be measured over the temperature range 760 to 1200°C (1). By contrast it may also be necessary to take stress measurements at liquid hydrogen temperatures.

Therefore alloys which are selected for use as high temperature strain gauge materials must possess the following overall properties:

[a] **Electrical Properties:** the alloy should have a high electrical resistivity and a low temperature coefficient of resistance and the alloy wires should have little thermal output dispersion. The resistance/temperature relationship of the alloy should remain linear over the range of operating temperatures and be reproducible after many cycles of heating and cooling. The alloy should have a stable and reproducible electrical resistance when exposed to operating temperatures for long periods of time, which is to say that the alloy must have good resistance to oxidation.

[b] **Elastic-Electrical Properties**: the alloy should possess a high sensitivity to strain which should remain constant over the whole strain range and the strain sensitivity/temperature relationship of the alloy must be linear and be reproducible.

[c] **High Temperature Mechanical Properties**: the alloy should have little mechanical hysteresis under operating temperatures and retain a high elastic strain limit and high fatigue strength.

There are different requirements for the properties of the materials used in a wire resistance strain gauge depending upon the particular use of the strain gauge, for example, if the gauge is

Table I Properties of Alloy Systems of Gold, Palladium and Platinum			
Alloy	Electrical resistivity, μΩ cm	Temperature coefficient of resistance, $\times 10^{-6}/^{\circ}C$	Strain sensitivity, $(\Delta R/R\varepsilon)$, K
Au	2.19	4000	3.22
Au-Ag	10	700	–
Au-Ag-Pt	17.5	700	–
Au-Pd	41	302	1.8
Au-Pd-Fe	158	~0	2.7
Au-Cr	36.9	11	–
Au-Pd-Cr	71.5	12	–
Au-Pd-W	85.5	47	–
Au-Pd-Mo	100	–120	–
Au-Ni-Cu	142	420	–
Pd	10	3800	6.6
Pd-Cr	100	375	1.6
Pd-Mo	104	135	1.6
Pd-W	68	168	5.1
Pd-Ag-W	40	~0	1.25
Pd-Rh-Ru	87	750	–
Pd-Ru-Mo	42	150	
Pd-Ag-Pt	38	15	–
Pt	9.81	3927	4.84
Pt-8W	59	246	3.7
Pt-8.5W	62.5	140	3.7
Pt-9.5W	76	139	3
Pt-W-Re	89	82	2.4
Pt-33Ag-3W	46	~0	–
Pt-9Rh-9Mo	67	222	26
Pt-Rh-Os	28	730	4.7
Pt-Rh-W	40	400	–
Pt-Pd-Ir	49.7	250	4.3
Pt-Pd-Rh	30.1	556–657	4.3
Pt-45Pd-10Mo	78	100	4
Pt-20Mo	104	135	1.6

to be used to measure high temperature static or quasi-static strain, then the requirement for good electrical properties is emphasised, that is, the alloy should have a stable structure and possess good resistance to oxidation. If the gauge is to be used to measure high temperature dynamic strain, then the alloy must retain a high sensitivity to strain and have good fatigue strength; while if the alloy material is to be used in various sensors for measurements at room temperature then the alloy should possess high electrical resistivity, a high strain sensitivity, high strength but have little mechanical hysteresis. Thus the different requirements for strain gauge materials and the many applications to which they can be put have made this a very complex field of study.

Background to the Study of Strain Gauge Materials

The study of resistance wires began in 1856 when Thomson discovered the phenomena that the electrical resistance of a metal would change with the stress it experienced (2). Much of the pioneering work was done in the 1960s by Bertodo of Bristol Siddeley Engines Ltd. who systematically studied forty-five binary and ternary alloy systems, and concentrated upon platinum-tungsten alloys (3–6). At the same time extensive studies were being conducted on dilute alloys of platinum and tungsten by Easterling (7), Maddocks (8), Sidhu (9), McCalvey (10) and Grindrod (11). The results of the studies showed that the most promising alloys were dilute platinum-tungsten alloys containing 8.5 to 9.5 weight per cent tungsten. These alloys have a single phase at all temperatures and they possess all the characteristics required of high temperature strain gauge alloys, with the exception that they have a slightly high temperature coefficient of resistance. Subsequently a high temperature strain gauge was made using resistance wires of platinum-tungsten alloys (12).

In 1962 Pravoverov and Savitskii studied (a series of) alloys containing gold-35 per cent silver-5 per cent platinum and palladium-35 per cent silver-5 per cent tungsten. These alloys have a comparatively low temperature coefficient of resistance, especially the palladium-35 per cent silver-5 per cent tungsten alloy, where the temperature coefficient of resistance is almost zero over the temperature range 100 to 700°C, but they could not be used because of their poor resistance to oxidation (13). Agushevich worked with the RC22 type alloy which had improved stability in its electrical resistance compared to the platinum-tungsten alloy (14).

In 1967 in the United States the ternary alloys platinum-rhodium-osmium, platinum-palladium-iridium, platinum-rhodium-molybdenum and platinum-palladium-rhodium were examined, all of them having a comparatively high strain sensitivity, a high temperature coefficient of resistance but poor structure stability (15). Bertodo pointed out in 1968 that the platinum-45 per cent palladium-10 per cent molybdenum ternary alloy was the best high temperature strain gauge alloy available then (16). Table I lists the properties of all these alloys.

Three platinum alloys: platinum-10 per cent nickel, platinum-8 per cent nickel-2 per cent tungsten and platinum-8 per cent nickel-2 per cent chromium having excellent stability and resistance to oxidation were reported by Bean in 1969 (17). The maximum temperature they could be used at was 1400°F (760°C). He suggested that the platinum-8 per cent nickel-2 per cent chromium could be used as compensating wire. These alloys are listed in Table II.

During the 1970s and the early part of the 1980s, hardly any alloys emerged as new high

Table II

Properties of Some High Temperature Strain Gauge Alloys

Alloy	Electrical resistivity, μΩ cm	Strain sensitivity, K	Temperature coefficient of resistance, $\times 10^{-6}$/°C	Apparent strain, με/°F	Note
80Pt-20Cu	36–56	2	250	125	unstable
80Pt-15Cu-5Ni	73–74	2.1	150	71	> 1000°F, unstable
80Pt-15Cu-5W	unworkable	–	50	–	unstable
90Pt-8Cu-2W	53–57	2.4	200	83	> 1000°F, unstable
90Pt-5Cu-5W	unworkable	–	220	–	–
90Pt-10Ni	32	4.2	630	15	1400°F
90Pt-8Ni-2W	31.3	4.2	680	162	1400°F
90Pt-8Ni-2Cr	38	4.1	440	107	1400°F
90Pt-5Ni-5Cr	unworkable	-	1700	–	–
80Pt-5Ni-15Cu	23–29	2.1	150	71	> 1000°F, unstable
92Pt-8W	55–59	5.3	210	40	1400°F
90Pt-2W-8Cu	53-57	2.4	200	83	> 1000°F, unstable

Table III
Comparison of the Properties of Platinum-8 wt.% Tungsten Alloy

Year and reporter	Temperature coefficient of resistance, $\times 10^{-6}$/°C	Electrical resistance change per unit temperature %, over 20–800°C	Strain sensitivity, K
1963–64, Bertodo 1964–65 Bertodo 1965–66 Bertodo	246	0	3.7 ± 0.378
1963, Easterling	216	0	4.45
1963–64, Redfern	300	~ + 1 %	–
1964, Maddocks	~300	–	–
1965, Sidhu	324	+ 0.5 %	~4
1966, McCalvey	325	–	~4
1967, Grindrod	248	0	3.4
1973, IPM	220	good linearity, 0–700°C	3.7
1975, IPM	190	good linearity, 0–700°C	4.2

temperature strain gauge materials. However, in 1985 after an extensive search, the NASA Lewis Research Center identified palladium-chromium alloys as the best high temperature strain gauge materials for static strain measurement. They had studied a total of thirty-four palladium-chromium alloys and the alloy containing palladium-13 weight per cent chromium was found to have the optimum composition. An alloy with this composition has a lower temperature coefficient of resistance than alloys containing less than 13 weight per cent chromium, while alloys containing more than 13 weight per cent chromium have poorer resistance to oxidation (18). The Institute of Precious Metals has provided the NASA Lewis Research Center with palladium-13 weight per cent chromium alloy wires, of diameter 25, 76 and 500 μm.

Chinese Developments of Noble Metals Material for Strain Gauges

As a result of strain gauges now being used to measure static and dynamic strain in engineering structures at temperatures up to 700°C, and with the urgent need for high precision sensors for specific applications, research work on the use of noble metals as strain gauge materials in China has greatly increased. From 1966 to the present there has been a huge amount of research work done in the Institute of Precious Metals (IPM).

The first stage of the work was from 1966 to about 1974, and the best noble metal high temperature strain gauge materials reported in the literature during this time were developed at IPM. These alloys were platinum-8 weight per cent tungsten, platinum-8.5 weight per cent tungsten and platinum-9.5 weight per cent tungsten. The properties of platinum-8 per cent tungsten alloys are listed in Table III.

In order to satisfy the requirements of the high precision pressure sensors, the production of the platinum-8 weight per cent tungsten alloy was thoroughly studied (19). Differing heat treatment procedures conspicuously affected the properties of the alloy. By using the earlier known procedure, the temperature coefficient of resistance of platinum-8 per cent tungsten alloy (as drawn) was determined to be 300 to 500 × 10^{-6}/°C; however after a special heat treatment this value was reduced to 200 × 10^{-6}/°C. The best heat treatment procedure known at present results in the following properties: a temperature coefficient of resistance of 267 × 10^{-6}/°C, (as drawn), and 190 × 10^{-6}/°C (annealed); a strain sensitivity of 5.2 (as drawn) and 4.2 (annealed), respectively, as shown in Table III. The currently used hot-drawing procedure has

Table IV

High Temperature Strain Gauge Materials Made of Noble Metals Developed at IPM

Alloy	Electrical resistivity, μΩ cm	Temperature coefficient of resistance, × 10^{-6}/°C	Strain sensitivity, K	Tensile strength, kgf/mm^2
Pt-8W	58	225	3.7–4.2	95
Pt-8.5W	62	191	3.7–4.2	100
Pt-9.5W	76	170	3.5	136
Pt-45Pd-10Mo	86	130	2.5	84
Pt-7.5W-5.5Re	82	113	3.2	137
Pt-8.5W-5Re-2Ni	77	171	3.2	135
Pt-8W-4Re-2Ni-0.5Cr	80.3	142	3.2	144
Pt-8W-4Re-2Ni-1Cr-0.2Y	73	160	3.2	105
Pt-10W-3Re-2Ni-1Cr-0.2Y	83	150	3.2	91
Pt-2Ni-1Cr	29	1000	–	43
Pt-2Ni-1Cr-0.2Y	29	977	–	43
Pt-20Ir-1Ni-1Cr-0.2Y	42	508	–	–

improved the mechanical properties and the metallurgical stability of the platinum-tungsten alloy over the range of operating temperatures.

After 1974 we began to develop new noble metal high temperature strain gauge materials. In order to obtain alloys which could measure static strain above 700°C and dynamic strain at 1000°C we directed our attentions to the deficiencies of the platinum-tungsten alloy. Platinum-tungsten alloy was considered to be the alloy having the best wire resistance at up to 700°C, but it was not suitable for measuring either static or dynamic strain in the temperature range 800 to 1000°C due to severe oxidation, evaporation and low fatigue strength. Therefore it was decided to improve its resistance to oxidation by alloying, and alloying elements close to platinum in the Periodic Table were chosen.

First, high melting point rhenium was added to the platinum-tungsten alloy to make the ternary alloy platinum-tungsten-rhenium. This resulted in an increase in the mechanical strength and a decrease in the temperature coefficient of resistance. However, the ternary alloy had poorer resistance to oxidation than the platinum-tungsten alloy. Second, elements, such as nickel, chromium, and the rare earth yttrium, which would be oxidised first and form a compact oxide film on the surface of the base alloy were chosen for use. These recently developed strain gauge materials are: platinum-tungsten-rhenium, platinum-tungsten-rhenium-nickel, platinum-tungsten-rhenium-nickel-chromium, platinum-tungsten-rhenium-nickel-chromium-yttrium and the compensating wires platinum-nickel-chromium, platinum-nickel-chromium-yttrium and platinum-iridium-nickel-chromium-yttrium. Their properties are listed in Table IV and shown in Figures 1 and 2.

It can be seen from the Figures that platinum-9.5 weight per cent tungsten has better resistance to oxidation than platinum-8 weight per cent tungsten. This is in agreement with the data obtained by Bertodo (3). The platinum-tungsten-rhenium alloy has a low temperature coefficient of resistance but poor resistance to oxidation, and the resistance drift at certain temperatures is too large. The temperature coefficients of resistance of platinum-tungsten-rhenium-nickel, platinum-tungsten-rhenium-nickel-chromium and platinum-tungsten-rhenium-nickel-chromium-yttrium alloys were lower than that for platinum-tungsten, and the alloys have greatly improved oxidation properties; there was only a slight decrease in strain

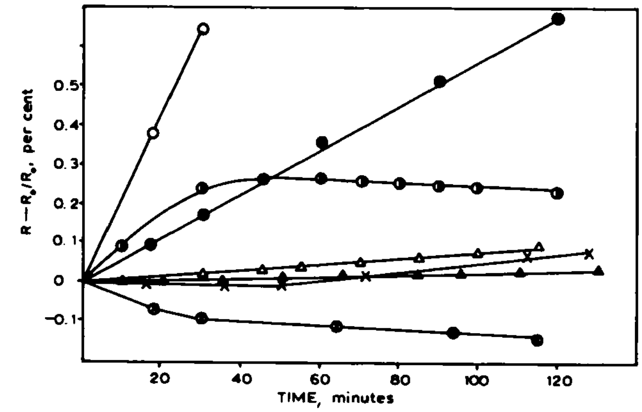


Fig. 1 The resistance drift at 700 and 800°C for wires made of platinum-tungsten series alloys with diameter 25 μm
○ Pt-W-Re at 800°C
● Pt-8.5W at 800°C
◑ Pt-W-Re-Ni at 800°C
△ Pt-8.5W at 700°C
× Pt-W-Re-Ni-Cr at 700°C
▲ Pt-9.5W at 700°C
⊗ Pt-W-Re-Ni-Cr-Y at 800°C

sensitivity. The zero drift at 800°C of platinum-tungsten-rhenium-nickel and platinum-tungsten-rhenium-nickel-chromium alloys is much smaller than that of platinum-tungsten and the electrical resistance of these alloys remained almost constant for 30 minutes. Alloys with the added rare earth element yttrium retained the properties of the platinum-tungsten-rhenium-nickel-chromium alloy and had improved linearity of the resistance/temperature relationship over the temperature range 800 to ~1000°C.

The platinum-tungsten-rhenium-nickel-chromium alloy and the platinum-tungsten-rhenium-nickel-chromium-yttrium alloys have been successfully fitted for the measurement of static strain at both 800°C and 900°C, and for also dynamic strain at 1000°C. These two alloys won the China Invention Awards in 1987.

The two newly-developed alloys: platinum-tungsten-rhenium-nickel-chromium and platinum-tungsten-rhenium-nickel-chromium-yttrium possess better properties than the established platinum-tungsten alloy, but their temperature coefficient of resistance is still high, and in practice they can only be used as temperature compensation gauges. This has limited their applications because of the difficulties found in making strain gauges and in using the compensation technique.

Therefore alloys are required which have good resistance to oxidation and a low temperature coefficient of resistance (approximately zero). After the gold-palladium-chromium alloy was developed for lead wire to be used in high temperature strain measurement it was found to

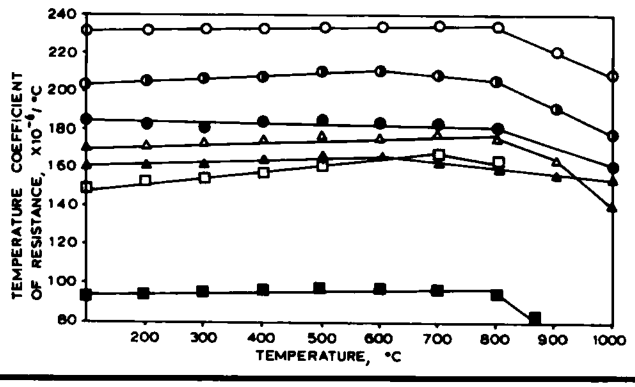


Fig. 2 Temperature coefficients of resistance are shown of the platinum-tungsten series alloys versus temperature
○ Pt-8W
◑ Pt-8.5W
● Pt-W-Re-Ni
△ Pt-9.5W
▲ Pt-W-Re-Ni-Cr-Y
□ Pt-W-Re-Ni-Cr
■ Pt-W-Re

Table V

Properties of the Gold-Palladium-Chromium Alloy System

Alloy	Electrical resistivity, μΩ cm	Temperature coefficient of resistance, $\times 10^{-6}/°C$, at 0–800°C	Strain sensitivity, K (room temperature)	Tensile strength, kgf/mm^2
Au-38.6Pd-3Cr	56	24	1.3	57
Au-37Pd-4Cr-2Ni	67	50	1.2	–
Au-35Pd-5Cr-5Pt-0.2Al	78	25	1.3	70
Au-38Pd-3Cr-1Al	62	300	1.4	–
Au-34Pd-6.6Cr-7Pt-2Fe-0.2Al-0.2Y	106	0–7	1.4	63
Au-32Pd-7Cr-7Pt-3Fe-0.2Al-0.2Y	118	–38	1.4	63.7

possess a very low temperature coefficient of resistance (20), good resistance to oxidation, and sufficient structure stability. Subsequently the gold-palladium-chromium series of high temperature strain gauge materials was developed and the properties are listed in Table V and shown in Figures 3 to 6.

The unique characteristics of seven-component gold-palladium-chromium-platinum-iron-aluminium-yttrium alloy, are as follows:

[i] When compared to platinum-tungsten alloy, it has a higher electrical resistivity and a much lower temperature coefficient of resistance, which can be adjusted from a positive to a negative

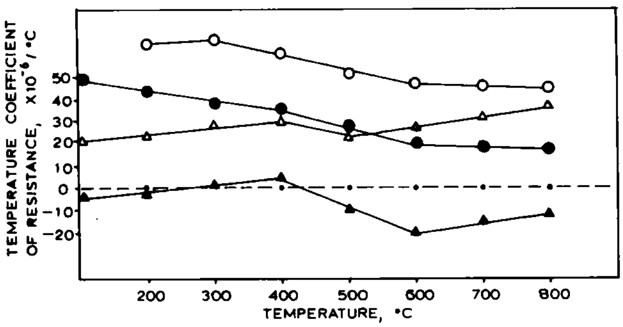


Fig. 3 The temperature coefficient of resistance of gold-palladium-chromium series alloys versus temperature
○ Au-Pd-Cr-Ni
△ Au-Pd-Cr
● Au-Pd-Cr-Pt-Al
▲ Au-Pd-Cr-Pt-Fe-Al-Y

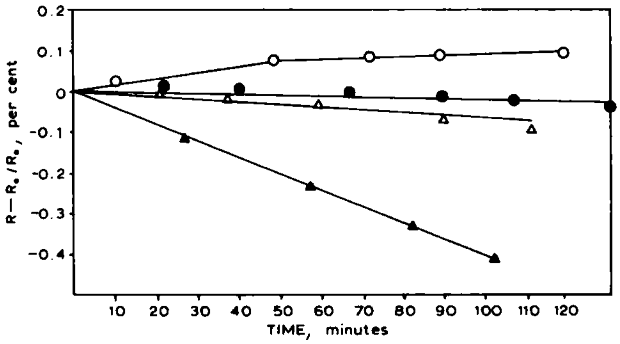


Fig. 4 The resistance drift at 800°C for wire made from the gold-palladium-chromium series alloys with diameter 30 μm
○ Au-Pd-Cr-Pt-Al
● Au-Pd-Cr-Pt-Fe-Al-Y
△ Au-Pd-Cr-Ni
▲ Au-Pd-Cr

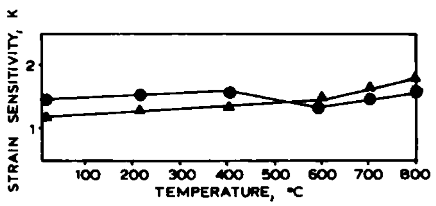


Fig. 5 Variations of strain sensitivity for alloys:
▲ Au-Pd-Cr-Pt-Al and
● Au-Pd-Cr-Pt-Fe-Al-Y, with temperature

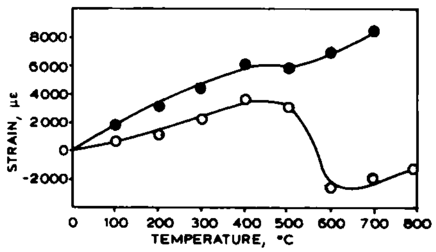


Fig. 6 Thermal output curves at 700°C, showing that after four subsequent cycles (upper curve) the reproducibility is within 130 με for:
● Au-Pd-Cr-Pt-Al alloy, and that for two subsequent cycles (lower curve) the reproducibility is within 100 με, for:
O Au-Pd-Cr-Pt-Fe-Al-Y alloy

value by changing the amount of iron. Also, the temperature coefficient of resistance remains almost the same over the temperature range 600 to 800°C and its resistance to oxidation is no worse.

[ii] At room temperature, the strain sensitivity of the alloy is low (1.2 to 1.4), but it increases with increasing temperature, so that at 800°C, the strain sensitivity has increased by 20 to 40 per cent and reached 1.7. This value can basically meet the requirement for the measurement of static strain. However, the strain sensitivities for platinum-tungsten and iron-chromium-aluminium alloys at 700°C have decreased by 20 to 30 per cent, respectively, as compared to the room temperature values.

[iii] On the thermal output curve there is a change at approximately 450°C, and there is a very good reproducibility. For the gold-palladium-chromium-platinum-aluminium alloy, after four subsequent cycles the reproducibility at 700°C is within 130 microstrain; while for the gold-palladium-chromium-platinum-iron-aluminium-yttrium alloy after two subsequent cycles the reproducibility is within 100 microstrain. This demonstrates that the structural change in this alloy is a reversible process and will not affect its stability.

The successful development of high temperature noble metal strain gauge materials having an adjustable temperature coefficient of resistance with a value around zero laid a solid foundation for making single wire self-compensated strain gauges or composite strain gauges. Thus, for example, the negative temperature coefficient of resistance of the gold-palladium-chromium-platinum-iron-aluminium-yttrium alloy can be co-ordinated with the positive temperature coefficient of resistance of the platinum-tungsten-rhenium-nickel-chromium-yttrium alloy or the iron-chromium-aluminium alloy to make a strain gauge so as to:

[1] increase the strain sensitivity of gold-palladium-chromium-platinum-iron-aluminium-yttrium and improve the linearity of changes in its temperature coefficient of resistance

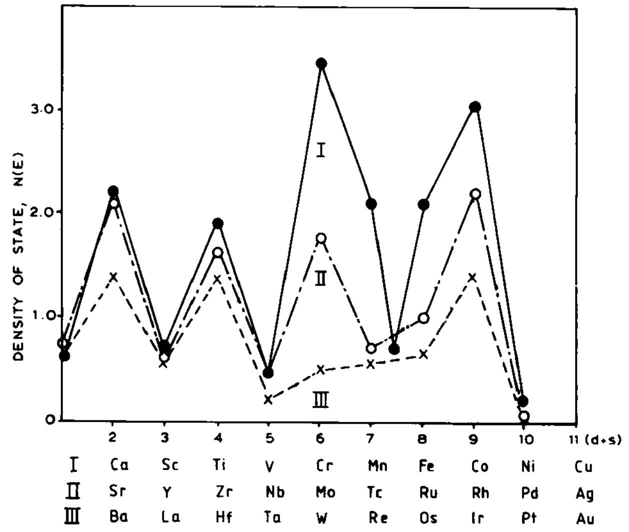
[2] decrease the thermal output of the platinum-tungsten-rhenium-nickel-chromium-yttrium alloy. A suitable co-ordination will produce a minimum thermal output. Such work is being undertaken in the Institute of Precious Metals, and the results look promising.

Prospects

It is very difficult to find resistance strain gauge alloys which can be used at temperature ranges above 900°C, whether noble metals or non-noble metals are used. As yet no noble alloy has been discovered which is capable of self-compensation. From the point of view of development, there should be no limit for recognition of the objective world. However, the reality presents a contradiction between the low temperature coefficient of resistance and the high strain sensitivity, since any factor which leads to a decrease in the temperature coefficient of resistance will induce a decrease in the strain sensitivity.

In order to obtain alloys having the largest strain sensitivity and a temperature coefficient of resistance which is approximately zero, the

Fig. 7 The relationship between the density of state (with the same spin direction) of I, II and III long period transition metals on the Fermi edge and the total number of outer shell electrons (d + s)



relationship between internal structure, the temperature coefficient of resistance and strain sensitivity must be studied.

Some researchers have designed new alloys using the electronic theory of metals (21, 22). Transition metals possess high electrical resistance due to the unfilled *d*-electron shell, which gives them a higher probability of *s-d* electron scattering. If it is assumed that the *s* and *d*-electrons of the transition metals and their alloys are totally centralised and subject to the Fermi distribution, then the Fermi edge of the transition metals would stretch across the entire *s-d* electron bands. The high density Fermi energy level means that these metals and alloys have high electrical resistivity. The temperature coefficient of resistance of the metals and alloys will increase with decreasing electrical resistivity, and when the electrical resistivity is at its maximum, the temperature coefficient of resistance will be at its minimum value.

The relationship between density of state N(E) and electron concentration e/a (or the total number of electrons in the outer shell q = s + d) of Groups I, II and III of the long period transition metals and their alloys is shown in Figure 7 (23). From the Figure we can say that if an alloy has a high density of state, and if the electron concentration falls in the following ranges: 2.5 ~ 3.5, 4.5 ~ 5.2, 6.5 ~ 7.2 and 8.8 ~ 10.2, then the temperature coefficient of resistance of this alloy would be small or approximately zero; see also Table VI (24).

Experimental results have proved this theory to be sound. The electron concentrations of our gold-palladium-chromium series of alloys have been calculated and measured values of their temperature coefficients of resistance are listed

Table VI

Compositions of Designed Alloys and Their Electronic Concentrations

Alloy composition, atomic per cent	Electronic concentration, e/a
Pt-28W	8.88
Pt-15Ti	9.1
Pd-20Mo	9.2
Pt-20Ta	9.0
Pt-20V	9.0
Pd-20V	9.0
Pt-10W-30Rh	9.3
Pt-22.5W-7.5Re	8.8
Pd-35Ag-3W	10.2
Pd-35Ag-3Pt	10.35

Table VII Electronic Concentrations in the Gold-Palladium-Chromium Alloy System and the Corresponding Temperature Coefficients of Resistance		
Composition, atomic per cent	Electronic concentration, e/a	Temperature coefficient of resistance, $\times 10^{-6}/°C$, at 0–800°C
Au-50.6Pd-0.0805Cr	9.61	24
Au-47.28Pd-10.46Cr-2.93Ni	9.97	50
Au-44.68Pd-13.06Cr-3.48Pt-1Al	9.81	25
Au-40.89Pd-10.24Cr-4.59Pt-4.59Fe-0.95Al-0.29Y	9.5	0–7
Au-37.99Pd-17.01Cr-5.83Pt-6.79Fe-0.94Al-0.28Y	9.41	–38

in Table VII. From the Table it can be seen that the electron concentrations of these alloys are all near the peak value of the optimum scale, so that the temperature coefficients of resistance are very low, especially for the seven-component gold-palladium-chromium-platinum-iron-aluminium-yttrium alloy, which has a temperature coefficient of resistance of 0 to $7 \times 10^{-6}/°C$.

In practice, increasing the content of an element in an alloy or adding new components to a certain alloy will produce some unwanted changes in the alloy. The method of manufacturing alloys must be improved from time to time.

Many methods of making amorphous alloys, such as the liquid metal injection wire drawing technique and the liquid metal rapid cooling rotation technique, must be used for those unworkable alloys to produce alloy in wire and foil form.

Conclusions

All in all, noble metals and their alloys are the most promising for use in high temperature strain gauges. These alloys should be platinum-, palladium-, and gold-based, and the alloy components should be elements from near Groups VIa and VIII in the Periodic Table, such as tungsten, rhenium, nickel, chromium, molybdenum, vanadium, iron, tantalum, hafnium. For alloys with higher resistance to oxidation and good overall properties, other alloying components should be chosen and sufficient attention given to trace additives of the rare earth elements, cerium and yttrium.

The Application of Noble Metal Strain Gauge Materials in China	
Year	Type, Constituents and Use
1973	WP-type high temperature strain gauge, Pt-8.5W and Pt, for measurement of rapid heating strain
1975	BNG-650 half bridge strain gauge, Pt-8.5W and Pt, for measurement of static strain at 650°C High precision small force pressure sensor, Φ 0.008 mm Pt-8.5W Acceleration sensor, Φ 0.025 mm Pt-8.5W
1976	Strain gauge, Φ 0.04 mm Pt-W-Re-Ni Measurement of dynamic strain of gas turbine blade at 1000°C
1977	Half bridge strain gauge, Pt-8.5W, Pt-W-Re-Ni and Pt-Ir alloy wires, for measurement of static strain at 700°C
1983	Strain gauge, Pt-W-Re-Ni-Cr-Y and Pt-Ir-Ni-Cr-Y, for measuring static strain at 800°C
1986	Strain gauge, Pt-W-Re-Ni-Cr-Y and Pt-Ir-Ni-Cr-Y, for measuring static strain at 900°C
1991	Strain gauge, Pd-13Cr and Pt, for measurement of static strain at 800°C (NASA Lewis Research Center)

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Platinum Cladding for High Temperature Alloys

Materials which retain their strength at high temperatures and remain ductile are needed for use in hydrogen-fuelled engines for hypersonic vehicles, in heat exchange tubes operated at 1260°C and combustion chamber linings. Molybdenum-based alloys can provide the strength at temperatures up to 1300°C, and adding rhenium improves ductility and lowers the ductile to brittle transition temperature. Molybdenum-47 weight per cent rhenium alloy is suitable, but rapidly undergoes oxidation in these arduous conditions. Therefore if protection from oxidation could be provided by a non-reactive and impermeable barrier its service life might be increased.

Researchers from NASA Langley Research Center in Virginia, U.S.A., have used platinum to clad the molybdenum-rhenium alloy, relying on its high melting point (1790°C) and chemical inertness at high temperature. (R. K. Clark and T. A. Wallace, *Scr. Metall. Mater.*, 1994, **30**, (12), 1535–1540). Disk shaped alloy samples were foil diffusion bonded with platinum of thickness 0.0178 cm, by placing each sample in a platinum sandwich, wrapping in graphite foil and applying hot isostatic pressure for 10 hours at 1094°C. Platinum cladded and unprotected disks of molybdenum-rhenium then underwent high temperature dynamic and static testing.

Oxidation effects on the alloy and interactions between alloy and cladding were examined, and while unprotected disks had catastrophic oxidation under dynamic oxidation at 595°C, the platinum cladding gave good protection from oxidation under both static and dynamic conditions for moderate times of 12.5 hours at 1260°C. The cladding also remained fixed to the alloy during the dynamic testing.

Rhodium in Glucose and Lactate Sensors

Amperometric enzyme microelectrode array strips are used to monitor clinical, environmental and industrial conditions, in particular to detect physiological substances such as glucose and lactate in small volumes of blood. Disposable sensor strips are used by diabetic patients to monitor their blood sugar levels. These sensors are manufactured by microelectronic technology using screen printing or lithography, with the reactive enzymes being immobilised in the microdisk pores by gel entrapment, cross-linking or covalent binding.

Now, researchers at the New Mexico State University have fabricated amperometric enzyme strips in a one-step electrochemical immobilisation using rhodium codeposited with enzyme to fix the enzymes in the pores of the disks. Rhodium lowered the overvoltage, giving very high specificity towards glucose, and offered not only an efficient way to retain the enzyme in the micropores, but also produced strong and preferential electrocatalytic detection of the liberated hydrogen peroxide, (J. Wang and Q. Chen, *Anal. Chem.*, 1994, **66**, (7), 1007–1011).

Using rhodium particles to fix the enzyme has removed the need for the membrane barriers and offers highly selective, fast and sensitive monitoring for mass produced reliable diagnostic strips.