Potentiometer Slidewire Materials

METALLURGICAL CONSIDERATIONS INVOLVED IN THEIR SELECTION AND DEVELOPMENT

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The slidewire potentiometer is a device intended to produce a signal voltage uniquely related to the mechanical displacements involved, and its materials of construction must provide therefore a reasonably accurate embodiment of the desired mathematical relationships. Noble metal alloys are usually selected for such applications because of their stability and freedom from corrosion. In this paper, based on a lecture given recently to the Control and Automation Division of the Institution of Electrical Engineers, some general correlations between electrical performance and metallurgical characteristics are discussed and it is shown how the application of these principles has led to the development of new and improved potentiometer slidewire materials.

Although it is axiomatic that resistance wires should have a high resistivity, prevailing circumstances will always determine the interpretation placed on this general requirement. Alloys with specific resistances ranging from 10 to 150 microhm-cm are fairly regularly employed and it is safe to say that high resistivity is frequently a subordinate consideration when the final selection of a slidewire material comes to be made.

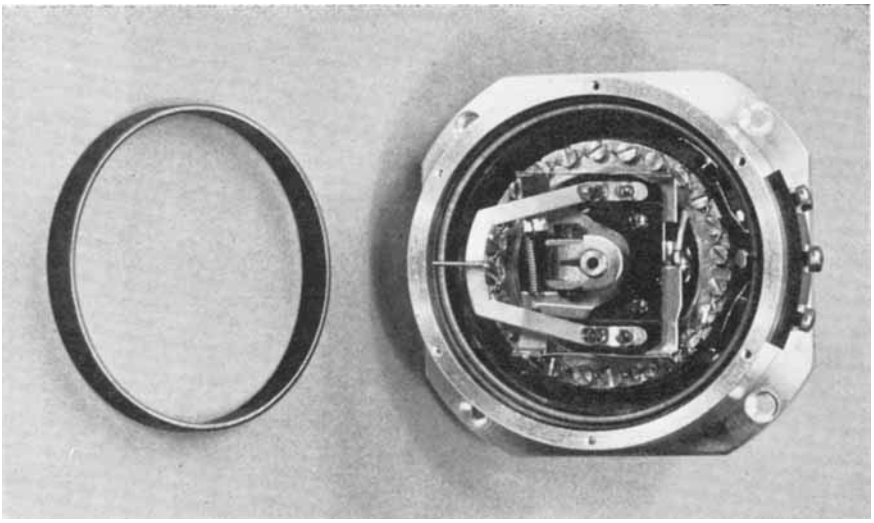
The balance finally achieved between the conflicting requirements of high resolution and minimum volume is generally determined by the qualities of electrical stability and mechanical permanence required from the component, and the importance of resistance constancy frequently overrides all other considerations.

Because of the obvious desirability of low and constant contact resistances, the use of noble metal alloys for precision potentiometers has become almost mandatory. The contact resistance provided by a particular slidewire/wiper combination is, however, dependent upon the load applied, so that we can sometimes envisage the successful use of base metals in those situations where high loads and torques are possible. As heavy loads accentuate the rate of wear on the slidewire this solution is of rather limited application.

A good deal of the voltage signal generated across a sliding contact manifests itself as electrical noise, and some of the traditional slidewire materials are successful because of their ability to keep this undesirable characteristic within tolerable proportions.

Potentiometers used in servo-mechanisms sometimes develop signals of several hundred volts and in such instances thermo-electric effects are small enough to be neglected. At the other end of the scale, however, are those slidewires used to sub-divide small fractions of a volt, where thermal potentials can introduce errors comparable in magnitude to the quantities being measured. Between these two extremes can be distinguished an area in which the main disadvantage of a high thermo-electric force is the 'hunting' effect which it can introduce when null points are being sought by automatic methods. A low thermal e.m.f. against copper is, therefore, important particularly in d.c. devices.

Pure metals have resistivities too low and temperature coefficients too high to permit



There are many different types of potentiometers, each requiring individual selection of the winding material to meet the specified performance of the instrument. This illustration shows a Colvern cam-corrected single-turn precision potentiometer and its toroidal winding. The wire in this case is 20 per cent copper-platinum

their effective use as slidewire materials. Higher resistivities and lower temperature coefficients can be achieved by suitable alloying procedures and the improved mechanical properties of the alloys facilitate winding techniques and ensure greater resistance to abrasion in service.

Composition and Resistivity

To assist in attaining the freedom from tarnishing necessary for low contact resistance, precision potentiometer alloys are generally based on either platinum or palladium. A discussion of the theory of alloying with respect to electrical properties is not within the present context, but it is worth considering a simple practical example, such as that afforded by the palladium-gold system, which illustrates many of the general principles employed.

Fig. 1 illustrates the effect of gold on the electrical resistivity and temperature coefficient of palladium. The specific resistance of pure palladium at 20°C is 9.93 microhm-cm, and its temperature coefficient of resistance is 0.0038 per °C. The addition of 20 per cent by weight of gold increases the specific resistance to 18 microhm-cm, and reduces the temperature coefficient of resistance by a corresponding amount. The peak resistivity is exhibited by the alloy containing 50 per cent by weight of gold although this does not

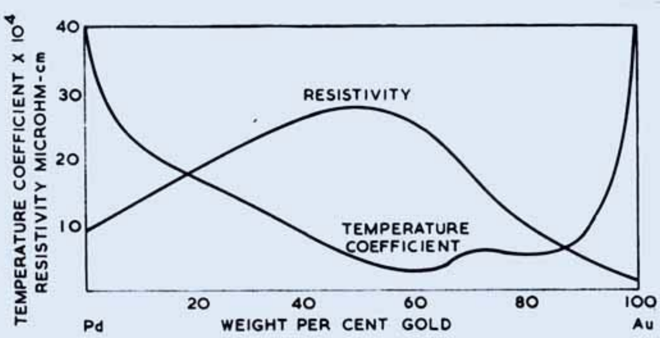


Fig. 1 Electrical resistivity and temperature coefficient of resistance of gold-palladium alloys

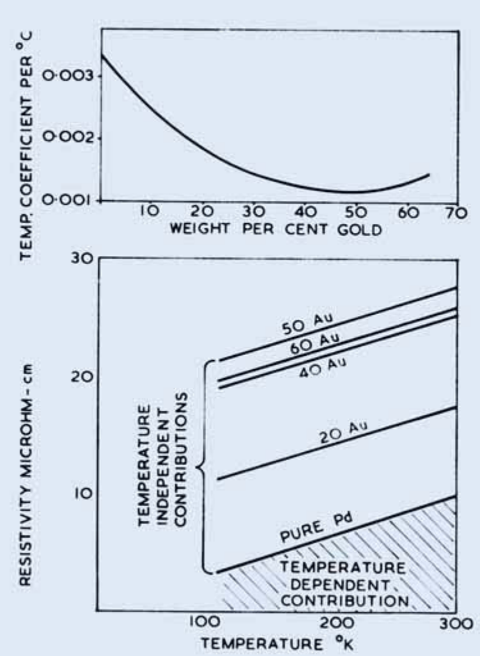


Fig. 2 Resistivity variation of gold-palladium alloys plotted as an illustration of Matthiessen's rule. The temperature coefficients were calculated from the elementary resistance model

correspond with the minimum temperature coefficient, which occurs at rather higher gold concentrations.

The gold-palladium system tends to be regarded as a classical example of one in which the two constituents are soluble in all proportions so that no discontinuous variation of properties with composition occurs. Although the slight inflexions exhibited by the two curves in Fig. 1 do indicate some departure from ideal conditions, the general implications are that high resistivity corresponds with low temperature coefficient and that the resistivity rises to a maximum at the highest degree of alloying. As long ago as 1860 Matthiessen suggested (1) that the total resistance of a metal or alloy should be separated into temperature-dependent and temperature-independent constituents. If we imagine that the alloying constituent is temperature-independent the situation can be represented graphically as in Fig. 2. Temperature coefficients calculated at 300°K from such an elementary model show roughly the same trends as those experimentally derived, although the numerical discrepancies suggest that these simple rules are not directly applicable to concentrated alloys.

The alloy containing 50 per cent of gold would be the most valuable to select for a resistance slidewire as its resistivity lies at the peak of the concentration curve. Slight variations in composition would be unlikely therefore to have much influence on the electrical resistance, and slidewires of constant diameter should show few problems due to non-linearity. The maximum resistance of gold-palladium alloys is, however, rather low for many applications and they are too soft to resist abrasion. The high thermal e.m.f.s they generate against copper could moreover be undesirable in certain precise work.

Silver and palladium form a continuous series of solid solutions. The peak resistivity of 42 microhm-cm is achieved with a silver content of 40 per cent by weight and this alloy has the remarkably low temperature coefficient of 0.00003 per °C. Where low noise values and steady contact resistances are matters of particular concern, this alloy is widely employed, and for really precise work its low temperature coefficient is of extreme value. Its mechanical properties are unfortunately rather lower than could be desired, and its resistance to wear and abrasion is not high. Since the low noise values appear to be a direct consequence of the low hardness, attempts to improve the mechanical properties of this valuable resistance material have usually resulted in inferior electrical characteristics.

Platinum Alloys

Platinum alloys containing approximately 70 per cent of silver were frequently used for slidewires in the early days of electrical technology. Although favoured because of its low temperature coefficient and moderately high resistivity, this alloy was difficult to make and had very variable properties.

Iridium-platinum alloys had far more reproducible characteristics and their electrical properties remained stable over long periods of time. Combined with an intermediate electrical resistivity of approximately 25 microhm-cm, the 10 per cent iridium-platinum alloy has an excellent resistance to tarnishing and corrosion and has high mechanical properties.

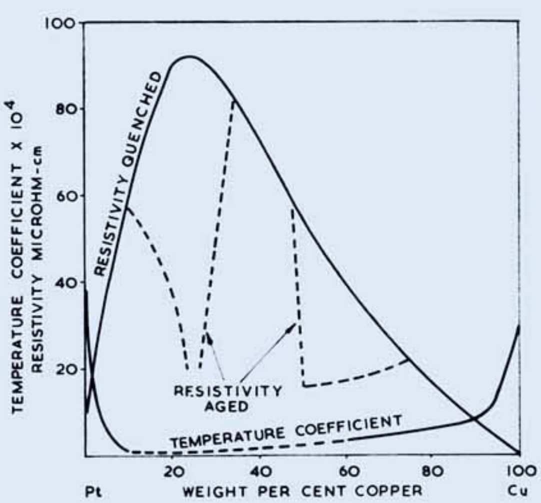


Fig. 3 Electrical resistivity and temperature coefficient of copper-platinum alloys

As an alloying addition, rhodium is less effective than iridium in increasing resistivity, although binary rhodium-platinum wires are still effectively employed in some low resistance potentiometers. The electrical properties of rhodium-platinum solid solutions are considerably improved by ruthenium additions, and the platium alloy containing 5 per cent of ruthenium and 15 per cent of rhodium is widely used for precise work where low contact resistance and freedom from wear is essential. This alloy has a specific resistance of 31 microhm-cm. and a temperature coefficient of 0.0007 per °C.

Copper and platinum form, at temperatures below the solidus, a continuous series of solid solutions, the electrical resistance of quenched alloys being as indicated in Fig. 3. The peak resistance of approximately 93 microhm-cm is exhibited by the alloy containing 24.5 per cent by weight of copper. This corresponds to the Cu Pt equi-atomic composition and a tendency to order makes this alloy somewhat unstable. Prolonged heat treatment of the quenched alloy between 200° and 300°C results in ordering; the copper and platinum atoms line up on alternate planes and the resistance falls from 93 to 14 microhm-cm. This tendency can be reduced to manageable proportions by moving away from the stoichiometric composition (2). The alloy now produced contains approximately 20 per cent by weight of copper and is stable at temperatures up to 200°C. Since this adjustment involved some sacrifice of resistivity and the alloy still had a base metal content rather higher than was thought to be desirable in a precision material of this type, there appeared to be considerable scope for a new noble metal alloy of higher resistivity and freedom from corrosion.

Palladium Alloys

Detailed literature and laboratory surveys showed that palladium alloys tended to develop higher specific resistances than those based on platinum or gold. In particular it was found that the highest resistances were obtained by alloying palladium with small quantities of the transition elements vanadium, chromium, niobium and molybdenum.

Tungsten-palladium alloys also have very high resistivities; 20 per cent by weight of tungsten produces an alloy having a specific resistance of 110 microhm-cm which can, unfortunately, be drawn into wire only with difficulty. As the chromium-bearing alloys, although ductile, tended to develop a coherent surface oxide skin and the reactive nature of vanadium and niobium make these elements difficult to add under production conditions, attention was therefore initially concentrated upon the molybdenum-palladium system.

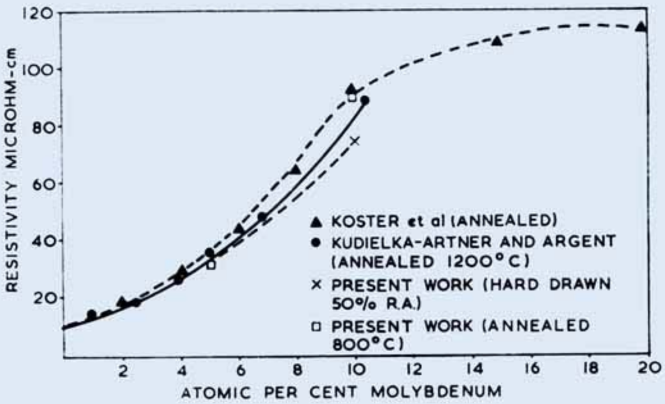
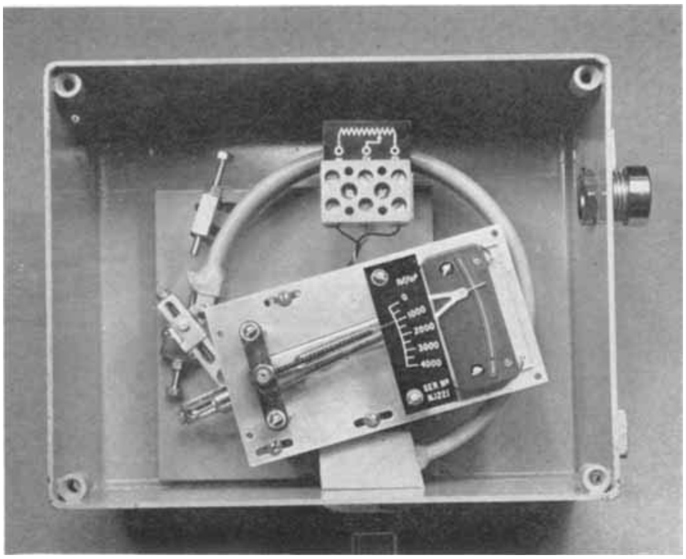


Fig. 4 Electrical resistivity of molybdenum-palladium alloys

The effect of molybdenum upon the electrical properties of palladium is illustrated in Fig. 4, which shows that resistivities of the order of 100 microhm-cm can be developed in a workable alloy which contains 10 atomic per cent of molybdenum. Higher resistivities were obtained by adding the molybdenum to a gold-palladium base. The composition finally selected for general purposes contained 5 per cent by weight of molybdenum and 40 per cent of gold, the balance being palladium (5). This material has a specific resistance of 100 microhm-cm which does not change appreciably either by working or heat treatment. Its temperature coefficient of 0.00012 per °C between 0° and 100°C is acceptably low for most purposes and its high tensile strength (approximately 70 tons per sq. inch in the hard drawn condition) ensures high wear resistance and ease of winding.

The routine production of vanadium-palladium alloys became a commercial proposition with the development of improved melting and fabrication techniques. The effect of vanadium on the electrical resistance of palladium is shown in Fig. 5 which illustrates some rather serious discrepancies between our work and that of earlier investigators



This precision potentiometer for a pressure transducer, by Delta Controls, is shown fitted to a Bourdon tube pressure gauge. The winding here is in 5 per cent molybdenum – 40 per cent palladium-gold

Accurate control of temperature coefficient of resistance is essential in the manufacture of precision resistance wires. This equipment, designed and built by Johnson Matthey, gives a continuous indication of temperature and resistance of fine wires over the range −60° to 250°C

(3, 4). This was because work hardening the alloys of higher vanadium content had the unusual effect of reducing the specific resistance to a significant extent. Small additions of aluminium reduced this effect considerably (6). The alloy selected for commercial evaluation contains 9 per cent by weight of vanadium and 1 per cent of aluminium. Combined with a specific resistance of 150 microhm-cm at room temperature is a temperature coefficient of −80 p.p.m. per °C and a tensile strength in excess of 50 tons per sq. inch in the annealed condition. Wire of this composition can be drawn down to diameters of the order of 0.0005 inch.

Contact Resistance

Some typical curves indicating the effect of load on contact resistance are shown in Fig. 6. The wiper used for these determinations contained 62.5 per cent by weight of gold, the remainder being silver and copper. These measurements were obtained at currents of ten milliamps. At pressures below three grams, contact resistance increases rapidly with decreasing load. Although this behaviour is observed with all materials there is no doubt that it is less pronounced with the softer resistance wires.

Sliding contact resistances are, very approximately, about twice as high as the statically obtained values shown in Fig. 6. Under sliding conditions contact resistance

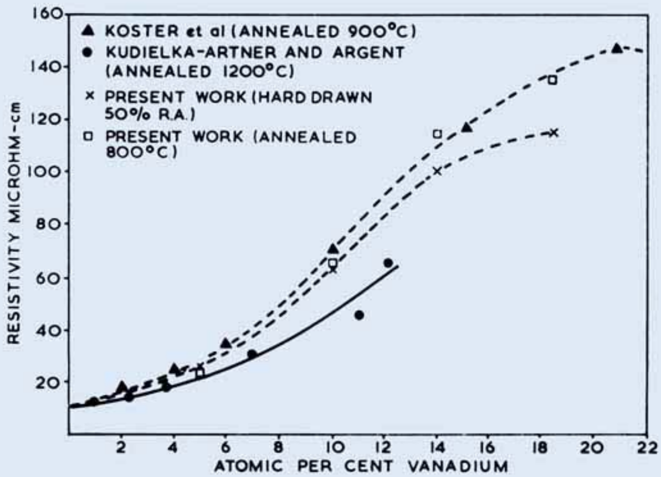


Fig. 5 Electrical resistivity of vanadium-palladium alloys

Typical Physical Properties of Noble Metal Resistance Wires								
Alloy	Specific Resistance		Temperature Coefficient of Resistance (0–100°C) per °C	Tensile Strength				Thermal e.m.f. against copper at 100°C mV
				Annealed		Hard Drawn		
	μΩ-cm.	Ω/circ. mil. ft		tons/in²	kg/mm²	tons/in²	kg/mm²	
10 per cent rhodium-platinum	19	114	0.0017	30	47	75	117	−0.10
10 per cent iridium-platinum	24.5	147	0.0013	35	55	80	125	+0.55
5 per cent gold-10 per cent rhodium-platinum	26	156	0.0011	40	63	90	42	−0.38
5 per cent ruthenium-15 per cent rhodium-platinum	31	186	0.0007	65	101	110	173	+0.03
20 per cent iridium-platinum	32	192	0.00085	45	70	105	165	+0.61
40 per cent silver-palladium	42	252	0.00003	24	38	70	110	−4.20
10 per cent ruthenium-platinum	42	252	0.00047	50	79	90	140	+0.14
8 per cent tungsten-platinum	62	372	0.00028	60	94	95	150	+0.71
5 per cent molybdenum-platinum	64	384	0.00024	60	94	90	140	+0.77
20 per cent copper-platinum	82.5	495	0.000098	38	60	90	140	−0.67
5 per cent molybdenum-40 per cent palladium-gold	100	600	0.00012	43	69	70	110	−0.19
9 per cent vanadium-palladium	150	900	−0.00008	50	79	90	40	−0.56

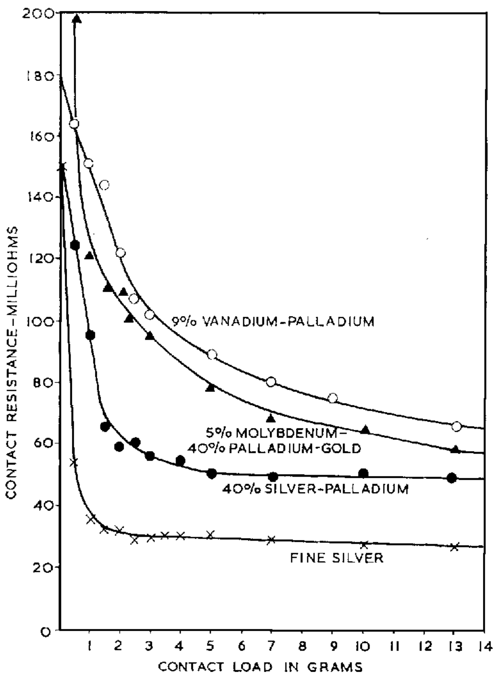


Fig. 6 Effect of a load on the contact resistance between a gold alloy wiper and fine silver, 40 per cent silver-palladium, 5 per cent molybdenum – 40 per cent palladium-gold and 9 per cent vanadium-palladium

and noise cannot be considered independently, and detailed studies now being undertaken should lead to valuable correlations between noise, load, contact resistance, and speed of sliding. A major difficulty in this work lies in separating the behaviour characteristics of the materials under test from effects which reflect the construction and design of the testing apparatus.

For purposes of comparison, contact resistance measurements were made on copper-nickel and nickel-chromium resistors. For noble metal slidewires, the relationship between load and contact resistance is well defined, but similar relationships are not observed with base metal slidewires. Although low contact resistances are sometimes obtained, load and contact resistance are not uniquely related and a very wide scatter of results is obtained. This scatter is undoubtedly associated with the high noise values generated between sliding contacts and base metal resistors. Noise and uncertainty increase rapidly as the contact load decreases and it is difficult, therefore, to obtain accurate results from low torque potentiometers wound with base metal wires.

Characteristics of Potentiometer Materials

The characteristics of a few of the main important potentiometer wires are summarised in the table. Of those listed the most noble and resistant to corrosion is the 20 per cent iridium-platinum alloy which unfortunately has a temperature coefficient rather higher than is acceptable in certain precision applications.

Because of their high catalytic activity platinum and palladium alloys sometimes cause difficulty when operated in atmospheres containing high concentrations of organic vapours. A recently developed rhodium-platinum alloy containing 5 per cent of gold does not readily promote low temperature organic reactions and might therefore be of considerable help in those applications where the danger of polymer formation exists.

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Frictional Characteristics of the Refractory Platinum Metals

A recent report by D. H. Buckley of the Lewis Research Centre (NASA Tech. Note TN D-4152, 1967, (Sept.), 1–15) conveys at first glance the impression that osmium and ruthenium, the hexagonal refractory metals, have, when rubbed against themselves, lower coefficients of friction than their cubic counterparts rhodium and iridium, and are therefore to be preferred for sliding electrical contacts. The author states dogmatically that 'from the results of this investigation, it would appear that ruthenium, with its hexagonal crystal structure, would certainly be highly superior to the face centred cubic metal rhodium in sliding electrical contact applications'. Detailed study of the paper, however, shows that this conclusion is based entirely on experiments made under ultra high vacuum conditions. The superiority of ruthenium over rhodium is only apparent at pressures below 10^{-8} torr and results reported show that at higher pressures rhodium has a much lower coefficient of friction than ruthenium. No information on the frictional characteristics of iridium or osmium at pressures above 10^{-8} torr is given in this report.

Within the context of space applications covered by NASA, it is perhaps logical to assume that atmospheric pressures below 10^{-8} torr constitute a perfectly normal ambient environment. Such clean conditions should certainly help when attempts are made to correlate surface properties such as friction with the crystallographic characteristics of pure metals. It is disappointing, therefore, to find in this report no indication of the purity of the materials studied or the way in which the test specimens were fabricated and prepared for examination. In subsequent publications it is hoped that fuller details will be supplied of the process, whereby the disc and rider specimens were 'finished to a roughness of 4 to 8 micro inches and then fully annealed'.

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