New Manufacturing Techniques for Precision Transformers for the L3 Coaxial Carrier System

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The critical function performed by the 2504A transformer in the L3 coaxial carrier telephone system necessitated the use of completely new materials and of methods radically different from those usually associated with carrier telephone transformer production. To satisfy operational requirements, extensive use has been made of parts machined from ceramic and glass insulating materials which can now be machined to very close dimensional tolerances. A description is given of the equipment and techniques which were developed to produce these transformers on a commercial basis, and their effectiveness is evaluated.

INTRODUCTION

Early in 1951 the Western Electric Company set up manufacturing facilities for the production of the L3 coaxial system.* This new system transmits the frequency band from 0.3 to 8.353 mc over coaxial cables. To counteract the attenuation of these cables, line amplifiers are provided every four miles. The 2504A transformer is used both at the input and output of these amplifiers to couple them to the cable. The system is designed so that the parasitic elements of the transformer are used to help shape the transmission characteristic. Since upwards of 2,000 of these transformers are used in a long cable system, it is necessary that the constants of each transformer be held to an extraordinary degree of precision, and that the temperature variation and aging effects be virtually eliminated.

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* L. H. Morris, G. H. Lovell, and F. R. Dickinson, The L3 Coaxial System, B.S.T.J., **32,** July, 1953. A technical description of the 2504A transformer appears on page 891.

To achieve the desired precision, a radically new type of construction was used for the 2504A transformer shown in Fig. 1. In place of the conventional windings, glass cylinders are used, having accurately machined grooves in which the conductor is embedded by a combination of firing and plating processes. Steatite forms are used to provide the housing. In turn, the manufacture of this transformer required the use of new tools and the development of new processes and techniques. The problem the

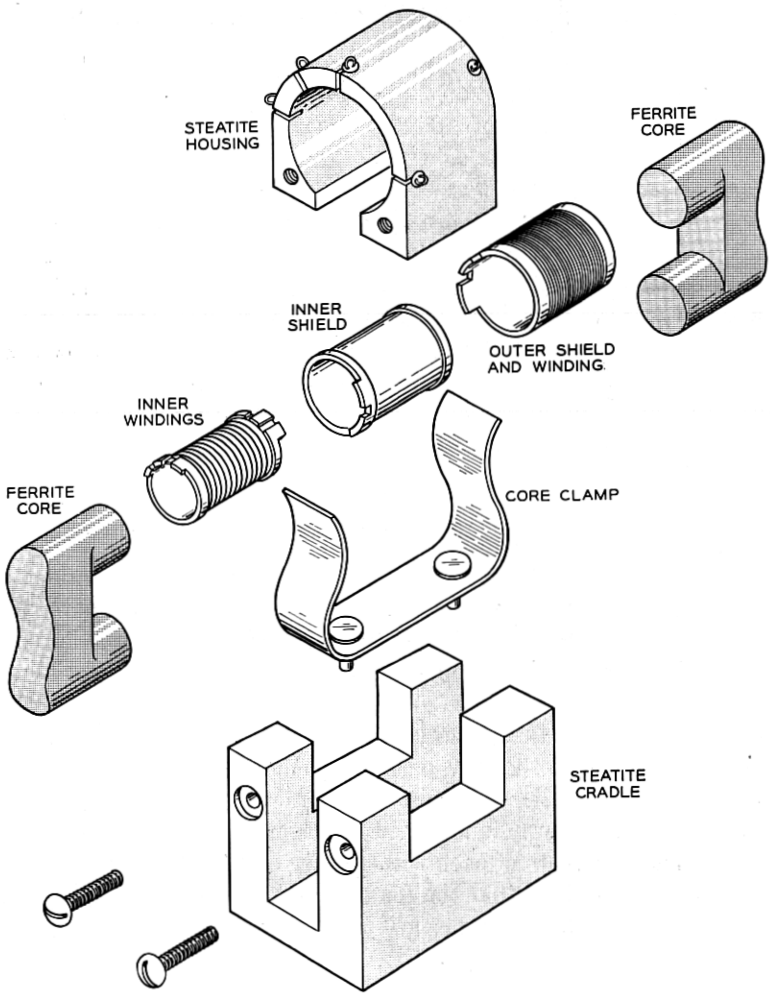


Fig. 1A — Exploded schematic of the 2504A transformer.

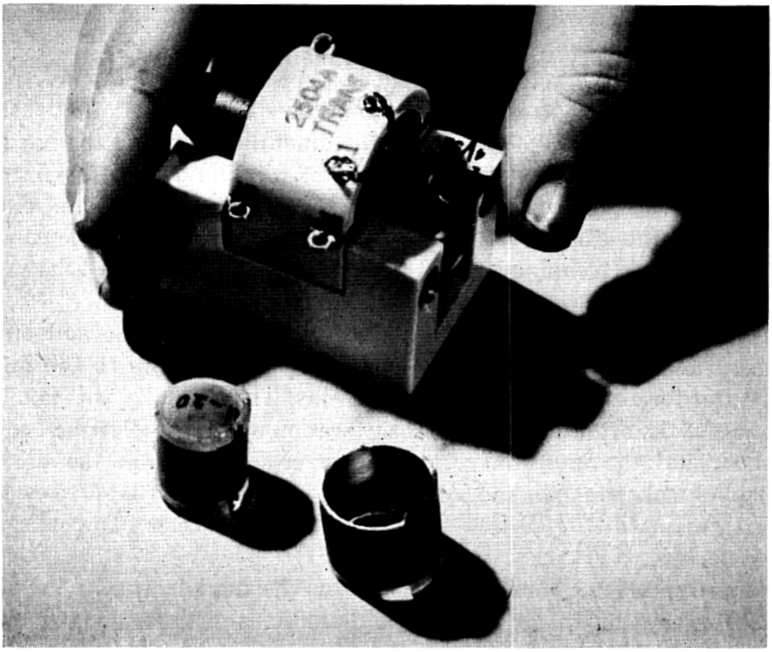


Fig. 1B — 2504A transformer.

engineer of manufacture had to solve, therefore, was how to set up to produce 2,000 such transformers a year on a capacity basis.

Table I gives a comparison of the structural details of the 2504A as compared to those of a carrier transformer of conventional design.

The new materials, in addition to having stability, low loss, and good insulating properties, can be held to very close mechanical tolerances, a condition which makes it possible to obtain the degree of electrical

TABLE I — COMPARISON OF STRUCTURAL DETAILS OF 2504A WITH THOSE OF A CONVENTIONAL TRANSFORMER

Part	Conventional Transformer	2504A Transformer
Core	Permalloy powder	Manganese-zinc ferrite
Winding form	Molded or fabricated plastic part	Threaded cylinders of special glass
Windings	Machine-applied insulated drawn copper wire	Plated copper embedded in special glass forms
Shielding	Copper or tin foil	Fired silver on special glass forms
Coil enclosure	Metal or plastic container	Steatite housing and cradle

precision required, once the techniques for performing the mechanical operations have been developed.

In the gage making art, equipment has been available for many years for grinding threads to tolerances comparable to the 0.031 ± 0.0005″ limits on the wall thickness between the inner diameter and the bottom of the threads of the glass form for the outer winding of the transformer and the 0.0005″ concentricity limits on the cylindrical inner and outer surfaces of the same part. However, considerable development was necessary before techniques could be worked out to hold such tolerances on fragile, thin-walled glass parts without excessive breakage.

Application of silver to the inner surfaces of the middle and outer forms, shown on Fig. 2, and the plated copper windings to the inner and outer forms presented similar problems. The difficulty was not the newness of the art, but the unusual surfaces on which the silver had to be applied, and the uniformity required in order to obtain the precise control of leakage fluxes and interwinding capacitances that was necessary to maintain the desired shape for the transformer's transmission characteristic.

Further problems were encountered by the manufacturing engineer in measuring some of the mechanical dimensions of the parts and some of the electrical characteristics of the completed transformer to the accuracy required and in arriving at a satisfactory correlation between changes in mechanical dimensions and the resultant changes in electrical properties that in the end were the characteristics that had to be held precisely.

MACHINING OF THE GLASS COIL FORMS AND THE CERAMIC CRADLE AND HOUSING

With the exception of a honing operation on the inside diameters of the coil forms and the final dressing operation after the parts are copper plated, all machining operations on the cradle and housing and on all three coil forms for the 2504A transformer are done on special grinding machines equipped with fine grit bonded-diamond wheels.

The configuration of the winding forms is shown diagrammatically in Fig. 2. These forms were originally made from fused quarts; but later, extensive tests showed that a cheaper 96 per cent silica glass, could be used interchangeably with the quartz. While the material is very hard, the parts themselves are thin and consequently fragile and easily distorted; so easily, in fact, that they can be distorted by more than the specified tolerance simply by holding them between one's fingers. This factor, together with the close dimensional tolerances including the concentricity requirement of ±0.0005″ on the outer winding form, made it imperative that tubing appreciably thicker than the finished product be used as the raw material for making the part. This made possible accurate honing of the inside diameters, used as the base point for hold-

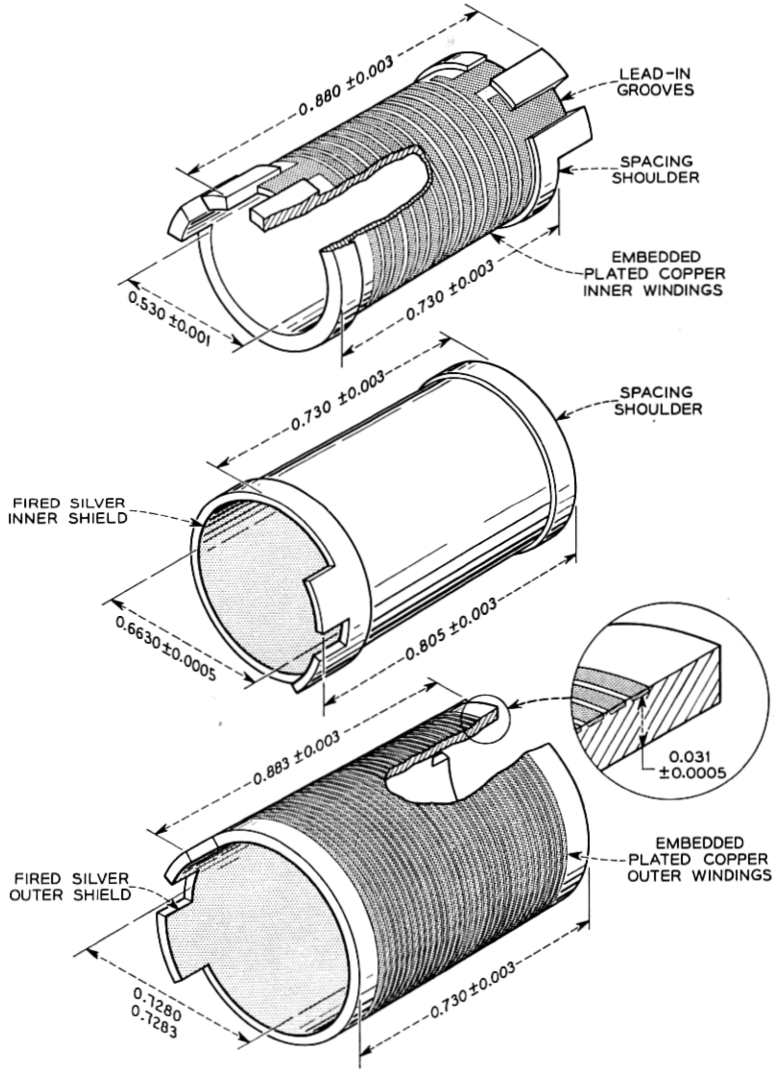


Fig. 2 — Composite view of winding forms, embedded copper windings and fired silver interwinding shields.

ing all other dimensions of the parts to the precise dimensions required. Though the specified tolerances on these dimensions were wider, in actual practice, it was found that holding the inside diameters to plus or minus 50 millionths of an inch made it much easier to meet the limits on other dimensions, particularly the highly important wall thickness dimension of the outer form.

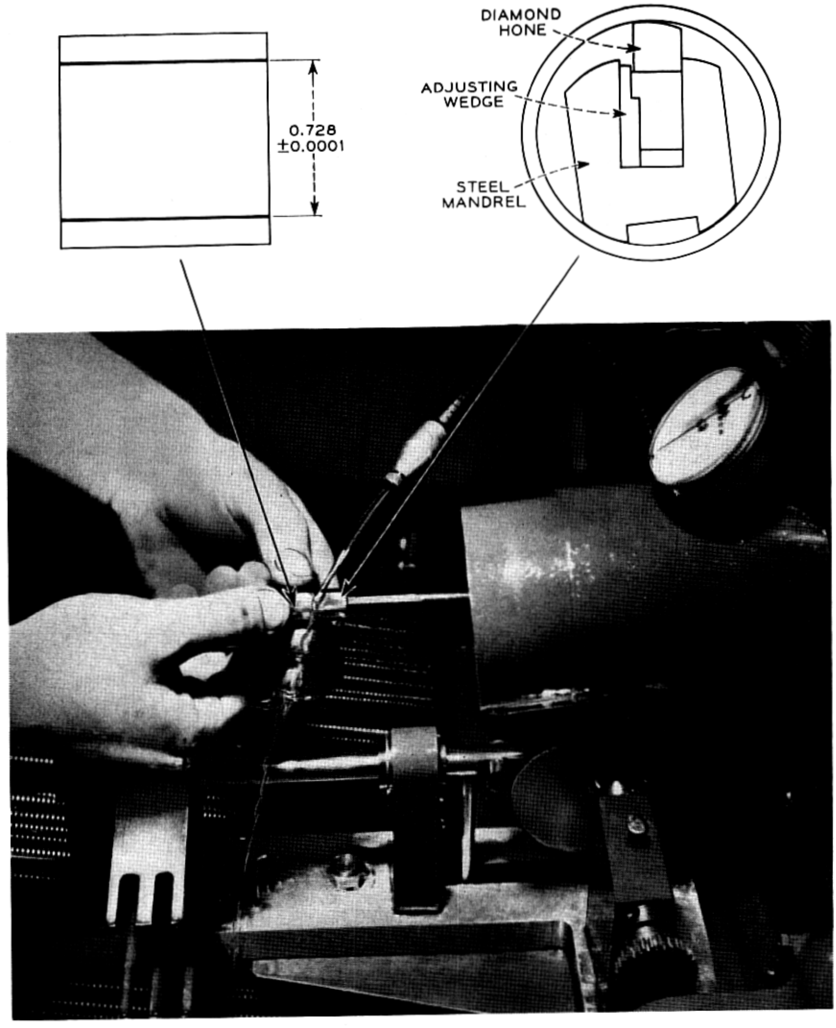


Fig. 3 — Honing inside diameter of coil form.

In preparing the tubing for this operation, the material is pre-shrunk in a plastic state at elevated temperatures around an accurately ground mandrel with the result that the bore is reduced to within 0.001″ to 0.002″ of its final size. The keyway required in the inner form is formed by the same process. No machining of this slot is required.

Rough grinding of the outside diameters to ±0.001″ and facing the

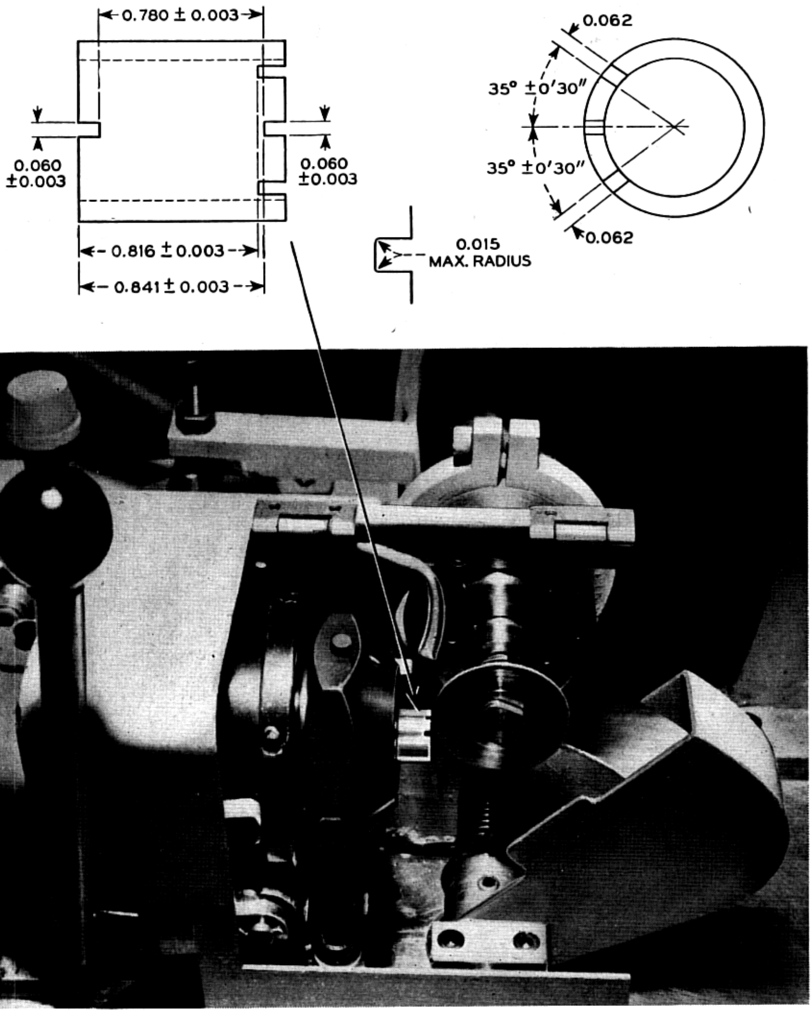
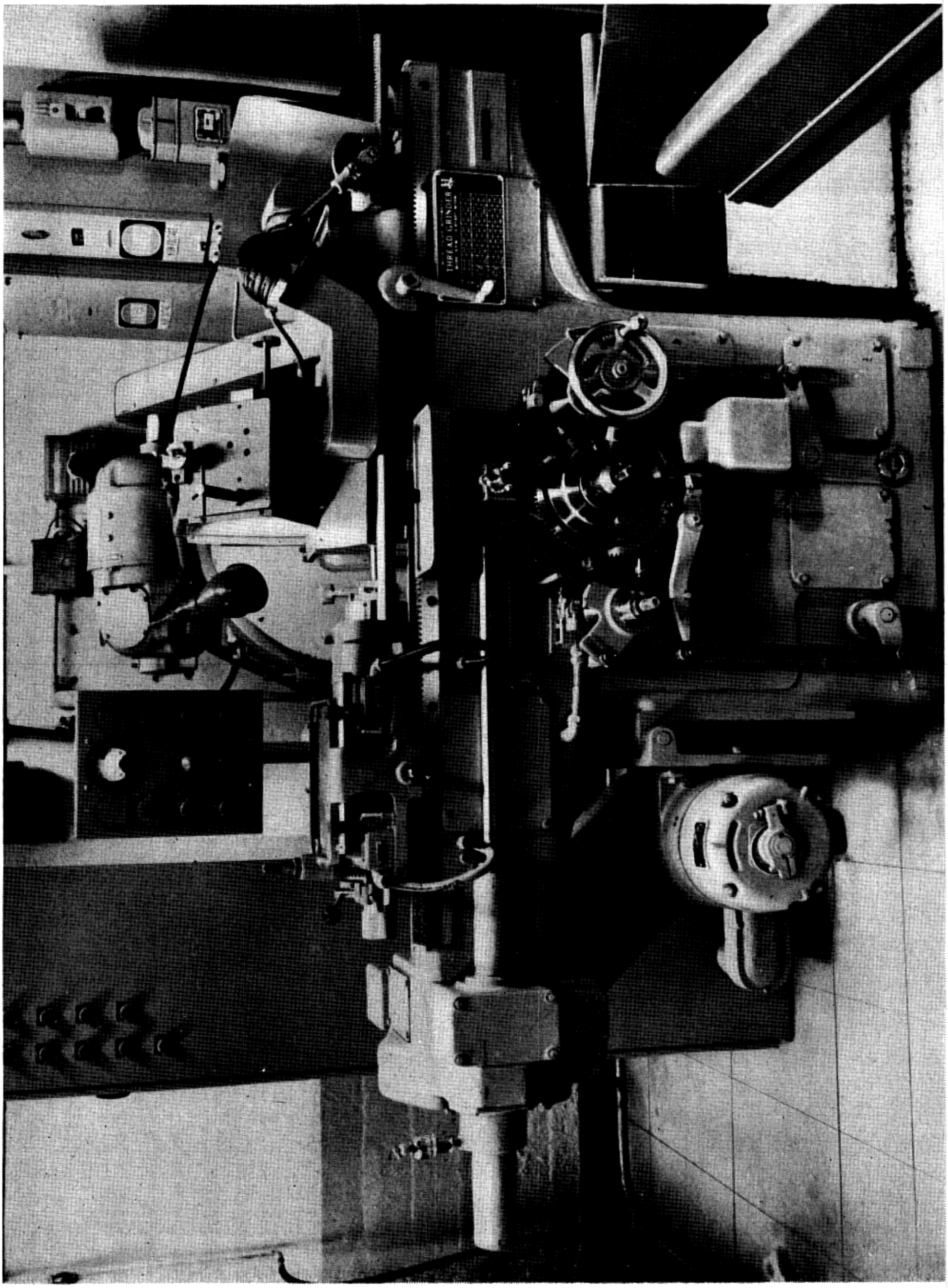


Fig. 4 — Cutting slots in end of inner form.


THREAD GRINDER

ends to meet the ±0.003″ tolerance for the overall length of the parts presented no particular problems. However, the use of an Arnold gage to give a continuous indication of the outside diameter during grinding of the parts was novel to coil manufacturing.

Three special machines, developed early in 1951, make the notching, slotting and trimming, necessary in forming the lead in grooves and tabs of which they are a part, a relatively easy operation, despite the fact that the tolerance in their angular location is better than ±1°. These machines — one of which is shown pictorially in Fig. 4 — contributed materially to the uniformity of the product, a factor of utmost importance in controlling the internal parasitics of the transformer.

Undercutting of the inner and middle forms for the spacing shoulders on these parts is a straight forward cylindrical grinding operation. Tolerances on the width of the shoulders are ±0.003″, while those of the diameter of the parts are ±0.001″.

Grinding of the threads on the inner and outer forms — the final operation prior to application of the plated copper windings — as had been anticipated — turned out to be a major manufacturing problem. Production of an experimental lot of transformers on a specially equipped toolmakers' lathe indicated that the best way to obtain the uniform control desired was through the use of an automatically cycled commercial thread grinder. Other methods, including a novel approach in which the threads were formed by a high-frequency vibration process using a powdered abrasive cutting agent, were either too slow or inherently did not have sufficient controls to yield the required uniformity. Even with the automatically cycled commercial thread grinder, considerable development was required to work out the required techniques for the process and only one supplier could be found who would undertake to work out the proposed machine modifications involved.

One of the problems was to adapt the grinder to permit use of a metal bonded in place of the resinoid bonded diamond or silicon carbide wheel conventionally used for thread grinding. Factors leading to the selection of the metal bonded diamond wheel were (1) the necessity for holding as nearly square a thread as possible — in practice a 14½° Acme thread with 0.0015″ maximum radii in the corners — and (2) the extremely hard abrasive nature of the material being worked. To permit use of these wheels, specially designed silicon carbide scrubbers had to be provided, built in to automatically dress the wheel to the shape required after completion of a predetermined number of parts.

Selection of the proper grain size for this wheel was also critical. Wheels much coarser than 300 grit — a size so fine it could be used to produce a high polish on metal parts — caused excessive chatter and breakage of parts when used to grind fine threads on glass.

The speed of approach and retraction of the wheel — controlled by a specially shaped forming cam — also had to be carefully worked out, not to minimize parts breakage alone, but to control thread over-

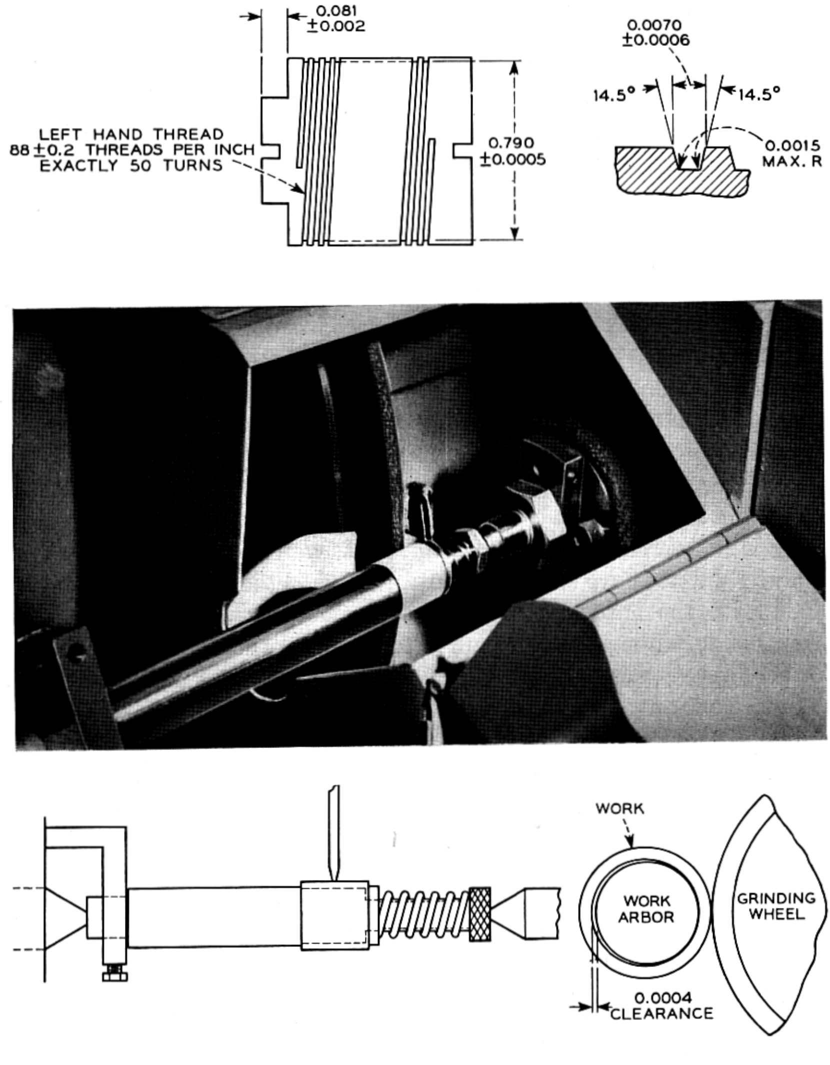


Fig. 6 — Cutting thread in outer winding form.

run, a factor affecting one of the transformer's parasitic interwinding capacitances.

Simultaneous removal of copper and glass in the final dressing of the parts after copper plating of the forms for the transformer windings required the selection of a wheel which could cut with very light pressure so as not to break the brittle glass form and at the same time not load up with copper from the windings. The most practical unit found for this operation was an "I" bond vitrified silicon carbide 220 grit wheel. Wheels with a stronger bond tended to cause excessive parts breakage, while softer ones broke down so rapidly that the required tolerances could not be held.

To provide as desirable operating conditions as possible, all of the grinding machines with the exception of one used for rough work were located in a dust free air-conditioned room in the basement of the building. In the case of the thread grinder, it was found necessary to take the further precaution of warming up the machine for a minimum of one and one-half hours prior to using it and providing more rigid guards in place of standard equipment in order to reduce vibration.

Machining of the steatite cradle and housing for the transformer presented problems of a similar nature. However, tolerances were not quite as critical and more information was available on commercial machining practices. As a result, not nearly as much development was required as on the glass winding forms. Procurement of unground parts sufficiently non-porous to avoid spalling and breakage of the housings, during firing after application of the sprayed silver shield on its inner surface, has been troublesome.

SILVERING AND PLATING OF THE GLASS AND CERAMIC PARTS

The inner surfaces of the ceramic coil housing and those of the middle and outer glass winding forms must be silvered for shielding purposes. The outer surfaces of the inner and outer coil forms are similarly processed to provide a base for the plated copper which, in combination with the silver, forms the actual coil windings.

It was imperative that these coatings be uniform in density and thickness particularly those on the inner surfaces of the coil forms. Thin nonuniform coatings result in intolerable variations in leakage inductance and interwinding capacitance, while excessively thick ones cause assembly difficulties. Other prerequisites were:

1. A strong dependable bond to the glass and ceramic surfaces.
2. Careful masking and process controls to insure that conductive

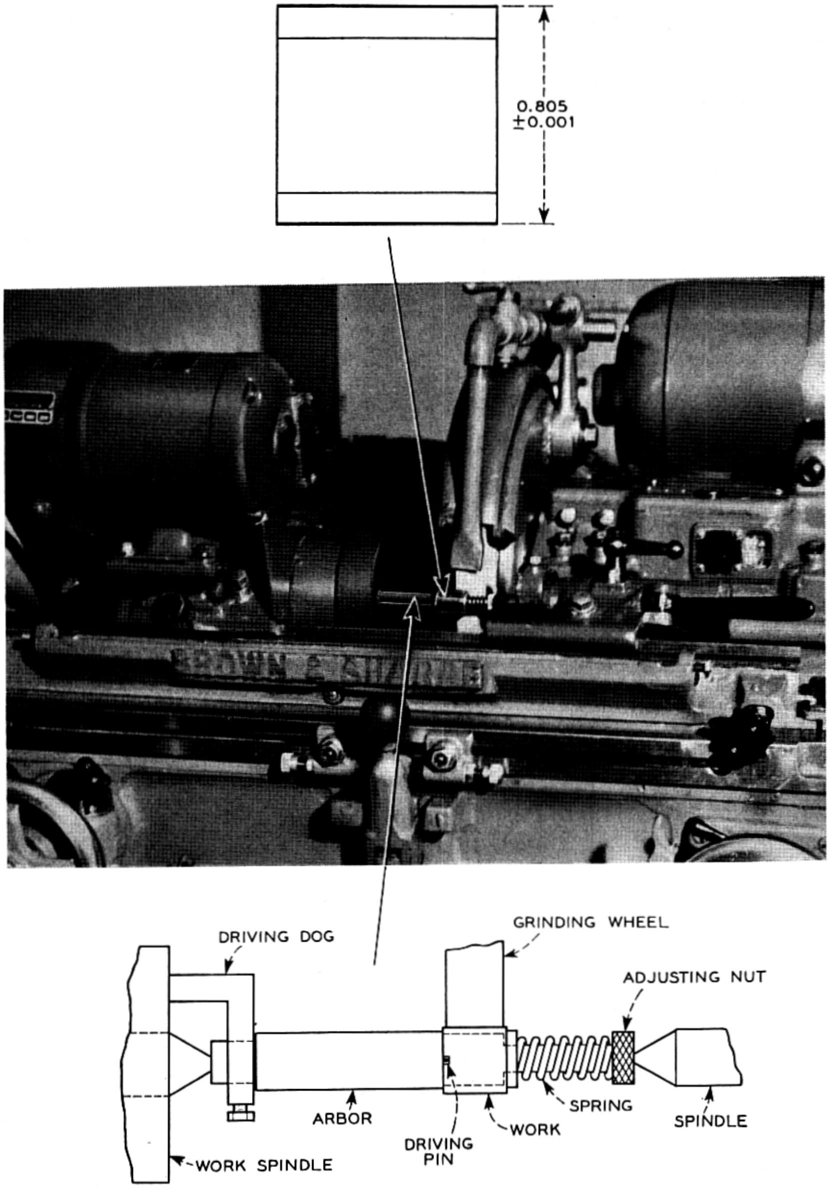


Fig. 7 — Grinding outside diameter of coil form.

material did not splatter onto critical areas where it might cause corona discharges while in service.

The silvering agent used was a finely ground silver powder suspended in a volatile organic solvent with small amounts of resin and glass frit. Sprayed on under controlled conditions in specially developed machines, the organic material is driven from the mixture by firing at 1250°F in a continuous belt furnace. At this temperature, the glass frit melts and wets the surfaces, bonding the silver securely to the glass and ceramic parts. Thickness of the coating is controlled by weighing control parts on a chain-o-matic laboratory balance before and after spraying and again after firing. Uniformity is improved by the application of multiple coats. However, not more than two can be used because of devitrification which results if quartz or high silica content glass parts are repeatedly fired at high temperatures.

In the early stages of production, the shield consisted of copper plating over fired silver coatings. This method required extra plating processes and prolonged the exposure of the parts to the plating solution. Since such solutions can attack the silver glass bond of the parts, plating of the shields was abandoned. To improve the continuity and conductivity of the coating, the parts are burnished in a specially developed machine which in a carefully timed cycle draws the inner surfaces of the parts spirally across the periphery of a rapidly rotating wire brush. Very good results have been obtained with the present process, the leakage impedance variation being reduced to plus or minus one-half of one per cent.

The threads which form the windings of the transformers are produced by plating copper on top of the silver fired on the outer surfaces of the inner and outer forms. The problem confronting the manufacturing engineer in this operation was that of applying as homogenous as possible a trapezoidal ribbon of copper in the narrow grooves on the outer surfaces without loosening the silver bonded to these forms.

This meant that the parts must not be permitted to remain in the plating bath any longer than absolutely necessary and that a well controlled process must be used to avoid bridging of the copper at the top before the groove is completely filled in the middle. To solve this problem, a plating process was used where initially the parts are given a flash of copper in a copper sulphate bath to protect the fired silver from attack by the copper fluoborate bath, subsequently used to permit rapid application of the heavy plating required. This flash effectively protects the silver from attack by the latter solution. To keep a fresh solution in the threads and to provide a uniform coating, the parts are rotated briskly during the plating operation. Because the quantity of parts being processed has not been sufficiently great to justify provision of a plant to provide continuously fresh plating solution, constant vigilance was required to keep impurities out of the solution. For this reason the anodes were enclosed in closely woven plastic bags and the solution was purified daily by filtering after treatment with activated carbon.

Microscopic analysis of etched cross-sections of the threads and dc resistance measurements on the overall windings indicated that exceptionally good results were being obtained by this process. Control is maintained by a continuous check of the winding for dc resistance.

PHYSICAL AND ELECTRICAL MEASUREMENTS

The performance of the transformer in its final state depends to a great extent upon the accuracy to which dimensions of the winding forms have been held. In fact, investigation has shown that half of the total variations in the overall transmission characteristic of the transformer can be attributed to variations in the dimensions of the outer form. Dimensional measurements on these parts thus becomes an extremely important consideration. Critical dimensions are the inside diameters of the three forms, wall thickness of the outer form at the root of the thread, and outside diameter of the inner form. Standard air, dial indicator and electronic gages provided have proven adequate for measuring these dimensions to the close tolerances required. Measurement of the wall thickness of the outer forms at the root diameter, however, has been very troublesome. The problem here is complicated by the fact that the measurement has to be made from a cylindrical surface in one plane to a point at the bottom of a narrow thread in a plane at the helix angle of the thread. At this point, the Acme thread is approximately 0.004″ wide including the 0.0015″ radii in each corner. The use of an optical comparator even at 100× magnification proved impractical because of the curved surfaces involved. After trial of this and other methods, some of them quite elaborate, it was found that the simple expedient of inserting a thin diamond blade in the thread and comparing the distance from the bottom of the blade to a circular rod supporting the cylindrical form with a flat ground carbide thickness gage gave the most consistent results. A diamond blade was used because it was found that the thin edge of the blade wore rapidly even with carboloy. A diamond edge lasts about six months. Results indicate that an accuracy of ±0.0002″ is attainable. While this accuracy is consistent with the ±0.0005″ limit on this dimension, greater accuracy would be useful in setting control limits. The strain gage used as the measuring instrument can be read to much greater accuracy. However, to date, no means has been found to obtain an improved method for contacting the surfaces to be measured.

Other mechanical measurements, while made to a degree of precision unusual in the coil manufacturing field, are of more or less routine nature and no particular difficulty was experienced in providing equipment capable of making measurements to the accuracy required.

The transformer was designed to require no adjustment to meet its specified electrical requirements, even though the requirements for the transformers' transmission characteristics were closer than those on all but a very few other designs even after adjustment. The phase and transmission set* provided for making these measurements is capable of a high degree of precision. However, to obtain the needed precision, an unusual amount of maintenance is required, the set being taken out of service for one day a week for this purpose. The set proved very useful in arriving at a correlation between transformer variations and those of the amplifier stage of which it is a part.

Special sets used for measuring the leakage impedance, the capacitance across the high impedance winding and the capacitance from the high voltage end of that winding to ground were very useful in controlling variations in the transformer.

CORRELATION BETWEEN TRANSFORMER ELECTRICAL AND MECHANICAL REQUIREMENTS

The purpose of electrical tests is to insure proper performance of apparatus in its end use and to provide process controls as an aid in meeting overall manufacturing objectives. Because of its unique mechanical construction and the precision to which the dimensions of its components are held, the first order causes of variation in the parasitic inductances and capacitances used to shape the transformers' transmission characteristics are under close control. Certain secondary causes of variation show up, however, which are quite different from those of the average carrier transformer. This is aggravated by the fact that the transformer is part of the amplifier feedback circuit and in consequence, certain parasitic capacitances have a much greater effect than they would have if the apparatus were used in a less complicated circuit.

Statistical control charts were very useful in meeting the test objectives on the 2504A transformer. Continuous control charts showed small

* D. A. Alsberg and D. Leed, A Precise Direct Reading Phase and Transmission Measuring System for Video Frequencies, B.S.T.J., **28,** p. 221, April, 1949, and D. A. Alsberg, A Precise Sweep-Frequency Method of Vector Impedance Measurement, Proc. I.R.E., **39,** p. 1393, Nov., 1951.

but very noticeable leakage inductance variations as measured at seven megacycles. Discovery of the reasons for the variations was not as obvious. Calculation showed that the possible contribution of the various factors in a commonly used formula for the total leakage inductance referred to one of the windings

$$L = \frac{10.6N^2 l(2\ Ct + a)\text{ henries}}{bc^2 \times 10^9}$$

where N = turns in the winding
l = mean length of turn for all windings
c = number of insulation spaces
t = thickness of insulation space
a = height of window opening
b = width of winding

was too small to account for the variations experienced, small though they were by comparison with those of conventional transformers. The number of turns in the windings and the number of insulation spaces being automatically fixed and charts of other factors indicating adequate control focused attention on the assumptions used in arriving at the formula expressed above. One of these — the assumption that the leakage flux is uniform and parallel to the axis of the core — provides the clue to the variations. A certain amount of flux must intercept the shields and set up eddy currents. Differences in the effective thickness of the shields were found to be major contributors to leakage impedance variations. This led to the establishment of the elaborate controls on the spraying process described earlier in this article.

Control of parasitic capacitances presented a somewhat different problem. While the interwinding capacitances of the transformer are complexly interrelated, charts kept for control purposes showed fair correlation between the wall thickness of the outer form and the capacitance across the high impedance winding. Possibly greater correlation could have been obtained if the average wall thickness could have been arrived at through a weighted integration process. Despite the fact that the data were not entirely adequate, a number of irregularities in mechanical processes were discovered as a result of the keeping of control charts on this characteristic. Typical was the discovery of a worn condition on a carbide rod used for contacting the inner cylindrical surface of the outer winding for one of the gaging operations. Through continued use, a crescent shaped valley had been lapped out of the middle rod by the abrasive action of the glass parts in inserting them in the gage. As a result, a condition that might have gone undetected for some time was corrected before a large quantity of expensive parts were completed.

Numerous correlations similar to the two just described have been helpful in establishing manufacturing procedures on the 2504A transformer and have contributed a great deal to the setting up of satisfactory process routines.

ACKNOWLEDGMENTS

The co-operative spirit prevalent throughout the period while the manufacturing techniques for this unusual transformer were being worked out, a few of which have been described herein, has been very gratifying. Contributing to this were people in a wide variety of development and research groups at Bell Telephone Laboratories as well as many individuals in the engineering and operating departments of the Western's manufacturing organization. Among the many individuals involved, the efforts and suggestions of G. Bittrich, W. L. Brune, F. R. Dickinson, W. F. Janssen, C. W. Thulin, and A. W. Treptow of Bell Telephone Laboratories, and G. V. Craddock, A. Habif, F. J. Sweeney, A. R. Swenson, H. S. Wahlberg and operating supervisors P. Ferguson, L. G. Holt and R. H. Onyon of Western Electric's manufacturing organization were particularly helpful. With their help, processes at the end of the second year of manufacture are well stabilized with a defect rate in the final state of less than 5 per cent and a process breakage rate of tolerable proportion, a remarkable achievement considering the precision and unique processes involved.