# Spark Plugs---A Ceramic Industry

HOBART M. KRANER, Cer. E. '21

The rapidly increasing use of gasoline engines in automobiles previous to the war, and especially the importance of the airplane in the recent war, have made improvement of spark plug quality and design coincident problems with the improvement of the motors themselves. The function of the spark plug in the motor is vital to its perfect operation. It must therefore operate under all the various conditions in the motor to be of any value to it.

The service of the plug in the airplane motor is more severe than that in any other gasoline engine in present use, and it is toward the requirements of these engines that manufacturers are working. It will be well to consider the conditions under which these engines operate.

Temperatures alternate between those of 0°C. and those of 2500°C. at the rate of fifteen cycles per second. As a result of these temperatures variations existing in the explosion chambers only, the upper part of the plug is fairly constant at the slightly elevated temperature of the motor walls while the lower end undergoes rapid heating and cooling. This means that on the intake stroke in cold weather or at high altitudes the incoming gas and air may be as low as 0°C. while at the time of explosion the temperature may be 2500°C. Due to the fact that the cycle repeats so rapidly these extreme temperatures do not penetrate far into the insulator on account of the latter's poor heat absorbing and conducting properties. The resulting temperatures which exist fairly constantly in the insulator are, however, 70°C. in the containing jacket or shell, 200°C. in the central portion of the insulator, and 900°C. at the lower end of the insulator.* This will show that there are always unequal amounts of expansion present which cause strains in the insulating material. The unequal expansion between the metal shell and the insulator may also result in loosening of the insulator in the shell with consequent compression leakage.

During practically two-thirds of the cycle, reducing conditions exist in the explosion chambers which with a failure of a cylinder to explode will cause fouling from carbon deposit. This may be due to carbon already deposited in the cylinder or lubrication oil being broken down when sprayed against the hot plug. Pressures in the engine vary from less than zero to as high as 600 pounds per square inch.

*Causes of Failure*—The causes of failure during operation may be enumerated as follows and in order of the trouble given:

1. Fouling with carbon deposit causing short circuit. This is due to either a carbon deposit directly at the spark gap being held in place usually by a film of oil or to a deposit covering the entire lower end of the insulator, permitting the current to pass from the shell to the center electrode by way of this thin layer of carbon. Perfect combustion at ordinary altitudes would not permit this accumulation of carbon, but at higher altitudes where the density of air is much lower, the consequent rich mixture tends toward reducing conditions and carbon is deposited on the surface of the insulator. Should the mixture at any time fail to explode under these conditions, oil pumped in would gather some of this carbon together at the gap causing short circuit without the aid of previously-deposited carbon. Oil itself, although a good insulator, may be sufficiently broken down by the hot plug as to become a conductor of fair quality and is therefore apt to cause a short circuit when deposited at the gap or when coating the surface of the lower end of the insulator.

2. Fouling with oil across the gap causing open circuit. This trouble is usually encountered when the motor fails to start after a reasonable number of turns, or when it is recovering from a glide and explosions were not taking place in the cylinders. In both cases the motor pumps oil into the cylinders which is not removed by the action of the explosion. This is partially overcome by opening the throttle and permitting a number of explosions to take place during the glide or while landing. The resistance of pure oil uncontaminated by carbon is much higher than the same amount of air between the sparking points. If the voltage produced by the ignition system is lower than that necessary to produce breakdown in the oil, no spark will result.

3. Cracks developed in the insulating material. As mentioned above, the insulator is constantly under strains due to unequal temperatures. Pounding and vibration of the motor may in themselves be sufficient to cause cracks to be developed. In addition to these, the expansion of any metal parts in close contact with the insulator may be sufficient to break it. Cracks in themselves may not be serious or detrimental to operation, but dropping of any pieces of the insulator into the motor may result in serious consequences if not carried out by the exhausting gases. The exposed surfaces of the resulting cracks and the surfaces of ordinary cracks become coated with carbon eventually permitting enough shunt of current to preclude sparking at the gap.

4. Preignition. This does not occur frequently, and is often not recognized. When it does occur it is usually manifested by firing the incoming charge while the intake valve is still open, the exploding charge being fired back through the carburetor. Preignition also includes firing the incoming charge after the igniting current has been shut off. In this case no damage is done except that the cylinder continues to operate. It may or may not be due to the heat retained by the plug, although this is often the case with insulating materials of low heat conductivity such as mica. Mica itself is a flaky material usually producing an insulator with a rough surface. If any flakes

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project from the surface, they are apt to become incandescent and remain so for a sufficiently long period to ignite the incoming charge. An insulator of any other composition which tends to hold carbon on its surface may give the same trouble from flakes of carbon becoming incandescent and igniting the charge. For this reason a compact plug with smooth surface and without petticoats or other features which are apt to collect carbon is desirable. Other sharp projecting portions of the explosion chamber may also cause preignition.

5. Conduction through the insulator. This is of little importance except in the cheap glassy compositions, in very hot motors, or in case the ignition system is generating only sufficient voltage to produce a spark across the gap when unimpaired by leakage of the current through the insulating material. Leakage, however, is considerable in porus materials which absorb broken oil containing carbon in suspension, which makes it a good conductor.

6. Puncture of the insulator. This happens very seldom in actual operation of the motor, but it affords, along with leakage through the insulator at elevated temperatures, a good comparison of resistivity and adaptability of various insulating materials otherwise suitable for spark plugs.

Other troubles of consequence are corrosion and warping of the electrodes. Corrosion may be due to oxidation of the electrode by the intense heat developed and the presence at the time of oxygen in the chamber. It may also be due to the fluxing action between cements (which in some plugs are used to make an air tight seal between insulator and center electrode) and center electrode. The effect of the high voltage used often is to eat away a portion of the electrode, permitting this portion to drop into the motor with the possibility of serious consequences.

Warping is usually encountered in petticoat plugs or where the center electrode extends to a considerable depth below the supporting insulator. This results in closing the gap causing short circuit or in widening the gap a distance which will not permit spark by the voltage generated.

All of these troubles may be corrected to a certain extent by the change of design of the insulator, the composition of the insulator, or design of the other parts of the plug. The design of the insulator will depend considerably upon the composition of the material used. Inasmuch as the remedy of one trouble may bring on another, all we can expect is a compromise in favor of the more flagrant trouble.

Mica plugs have the reputation of high mechanical and dielectric strength at ordinary temperatures, but, being a hydrated silicate which loses water close to 1000°C., they become soft and friable in the hot motor due to dehydration. As mentioned previously, this material also gives trouble by preigniting the incoming charge and also having a rough surface which encourages the accumulation of carbon.

Glass molded plugs have been used, their chief advantages being tightness and more freedom from carbon deposits on their extremely smooth surface. These advantages do not however compensate for their extreme brittle nature and consequent liability to breakage in handling and under the extreme unequal temperature changes in the motor.

Most other patent compositions have the disadvantage of being either mechanically weak or sufficiently porus to permit absorption of oil and carbon developing short circuit. Porcelain alone seems to be the happy medium for spark plug insulators. This may be so compounded and burned as to meet the requirements in toughness, and recent developments have advanced dielectric strengths for all temperatures above most other suitable materials. Steatite plugs although giving high dielectric values for all motor temperatures are not superior to porcelain in toughness, and are impractical from the standpoint of commercial manufacture. Its vitrifying or maturing range is so short as to not permit its being burned in commercial kilns with sufficient accuracy to warrant its use.

To increase the insulation surface of the plug, petticoats are often used. The lower end of the insulator is of cylindrical shape, touching neither the shell nor the central electrode. The latter therefore extends unsupported and is liable to warping which may result in closed or widened gap.

Inasmuch as carbon deposit on the lower end of the insulators and electrodes causes fifty per cent of the trouble, insulators have been designed with the object of burning off the carbon deposit by maintaining hot portions which will accomplish this. These so-called carbon proof designs have sharp ridges on the lower end of the insulator where the carbon deposits, or sharp edged annular corrugations around the circumference at the lower end of the plug. The thin edges of these designs become incandescent for a sufficient length of time to assist in burning of the carbon at each explosion. In the hot motor of the airplane they cause preignition but have been in use in automobile motors for some time and give good service.

The design of the shell and electrodes is a problem of prevention of gas leakage, and breakage. The central electrode must be cemented or otherwise fastened in so that no compression is lost or breakage occurs due to the expansion of the wire. Cements are used which have sufficient resilience to permit the wire to expand under the extreme temperature changes without breaking the insulator. Some plugs use the electrode which is similar to a bolt, and being fastened in by a nut at the top. This means that the petticoat design is necessary to accommodate the head on the lower end of the electrode. It also means that pressure is always present at the point in the insulator where change of temperature also places strains. The plug in which the central electrode is threaded and cemented into the upper end of the porcelain is not so liable to breakage from this cause. The strain incident to holding the electrode in place is put upon the upper end of the porcelain which is uniformly heated throughout.

The so-called two-piece shell which permits taking apart for cleaning has several disadvantages which overbalance the advantage claimed for it. The cleaning of plugs should not necessitate taking completely apart. More plugs are broken in being taken apart for cleaning and retightening the insulator than are broken in actual operation. Considerable compression leakage is usually found in two piece plugs in which the insulator has been once removed and replaced. The passage of hot gas through the leaking channel causes increased heating of the insulator which in turn lowers its insulation value.

The plug in which the insulator is hot crimped or welded into the shell claims the advantage of perfect seal against gas leakage. It however has the disadvantage of not being renewable, but in consideration of the statement that many insulators are broken in unnecessary cleaning, this disadvantage is compensated for.

It was the writer's privilege to have been employed during the summer recess with three Ohio State ceramic engineers who are now well known in the spark plug insulator field; they are Taine G. McDougal, '11; S. J. McDowell, '17, and P. D. Helser, '17. The methods used in the particular plant with which they are connected will be briefly discussed, although methods vary with the different manufacturers and various materials used for insulators.

The preparation of the body consists of thorough grinding and mixing of the porcelain constituents with water to a creamy consistency, then removing all water in excess of that needed for plasticity. The plastic mass is kneaded on machines to remove all excess air and to give it proper homogeneity. The welded pieces are then ready to shape.

Grinding and mixing above referred to are accomplished in ball mills of the ordinary type. The "slip" as the ground mixture is called is screened through a standard 150-mesh screen to remove all the underground materials. That which passes the screen also flows past an electromagnet which removes any metallic iron which might have entered by way of an ingredient or other source. The slip contains approximately 75% water and must be relieved of two-thirds of this to make the clay of proper plasticity for working. By pumping into filter presses under high pressure, the water passes through canvas, leaving the clay in the press in the shape of a solid cake one inch thick and twenty-four inches in diameter. These cakes are removed and wedged or kneaded on specially designed machines for the purpose until the body is of uniform putty-like texture and all the air removed. It is then cut into convenient pieces for automatic compression into cylindrical blanks with a small hole through the centers.

The porcelain cylinder is then turned on lathes similarly to the manner in which wood or metal is turned, but of course on specially designed semi-automatic machines. Blanks are prepared by forcing the clay as taken from the wedging tables through a die, and at the same time making a hole through the center which finally is occupied by the center electrode. The blanks are partially dried in accurately controlled humidity driers until they are "leather hard" and in condition to stand the treatment of the turning tool. The turned insulator is allowed to dry to bone dryness, the imprint stencilled on the glaze applied.

Burning is done in a tunnel kiln similar to most tunnel kilns but of course having features making it adaptable only to the burning of such products. A tunnel kiln is a long brick tunnel in which a hot zone is maintained near the center. Steel cars well insulated by refractory materials carry the product to be burned gradually toward this zone. Gases passing out the stack at the charging end gradually heat up the ware which reaches maximum temperature in the hot zone. It is cooled down gradually after leaving the hot zone by air which enters at the discharge end of the tunnel. The operation is continuous and effects a saving of a high percentage of heat over the old intermittent process. Time and temperature varies in tunnel kilns but in high fire porcelains such as spark plugs the temperature in the hot zone is usually about 2642°F, the time required for such small pieces to pass through the entire length of the kiln being from 5 to 15 hours.

The porcelain is then ready for inspection after which the center wire is screwed into place along with special cement. These insulators are then welded into their proper steel shells under pressure with a copper-asbestos gasket against the bottom shoulder and a copper gasket against the top shoulder. The plugs are then tested for air leakage under 120 pounds per square inch and electric leakage with 10,000 volts.

The steel shells are turned and bored from hexagonal bars on automatic screw machines. They are then threaded and the side electrode welded on as a straight wire to be bent over after the insulator and shell have been assembled and after the air and electric tests have been made. At the same time that the side wire is bent into place, any excess center wire present is cut off. Further tests are conducted by the purchaser.