Spark plugs

The air/fuel mixture in the gasoline, or spark-ignition, engine is ignited electrically. Electrical energy drawn from the battery is temporarily stored in the ignition coil for this purpose. The high voltage generated within the coil produces a flashover between the spark-plug electrodes in the engine's combustion chamber. The energy contained in the spark then ignites the compressed air/fuel mixture.

Function

The function of the spark plug is to introduce the ignition energy into the gasoline engine's combustion chamber and to produce a spark between the electrodes to initiate combustion of the air/fuel mixture.

Spark plugs must be designed to ensure positive insulation between spark and cylinder head while also sealing the combustion chamber.

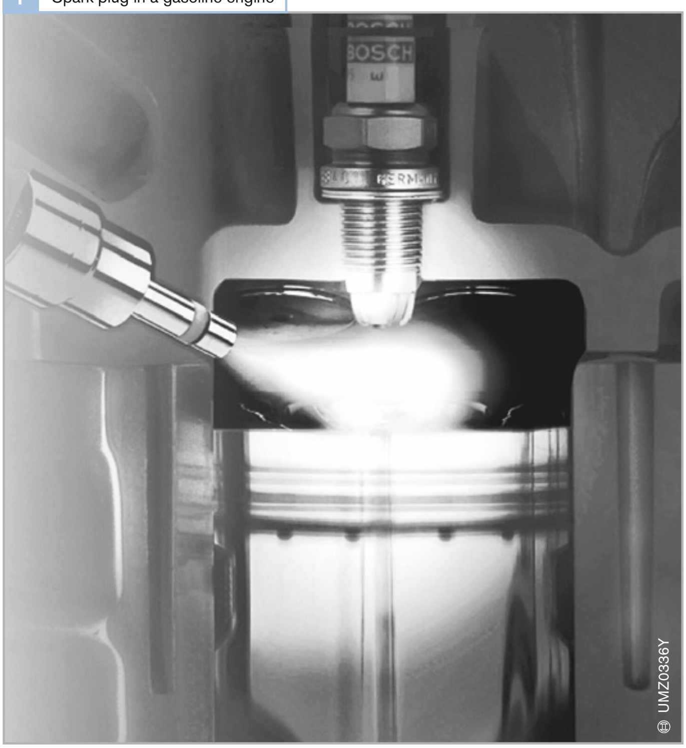
In combination with engine components, such as the ignition and mixture-formation systems, the spark plug plays a crucial role in determining operation of the gasoline engine. It must

- facilitate reliable cold starts,
- ensure consistent operation with no ignition miss throughout its service life, and
- not overheat under extended operation at or near top speed.

To ensure this kind of performance throughout the spark plug's service life, the correct plug concept must be established early in the engine-design process. Research investigating the ignition process is employed to determine the spark-plug concept that will provide the best emissions and most consistent engine operation.

An important spark-plug parameter is the heat range. The right heat range prevents the spark plug from overheating and inducing the thermal auto-ignition that could lead to engine damage.

1 Spark plug in a gasoline engine



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Usage

Areas of application

Bosch first used a spark plug in a passenger car in 1902, when it was installed in a system featuring magneto ignition. The spark plug then went on to become an unparalleled success in automotive technology.

Spark plugs are used in all vehicles and machinery powered by gasoline engines, both 2-stroke and 4-stroke. They can be found in

- Passenger cars
- Commercial vehicles
- Single-track vehicles (motorcycles, scooters, motor-assisted bicycles)
- Ships and small craft
- Agricultural and construction machinery
- Motor saws
- Garden appliances (e.g., lawnmowers), etc.

To accommodate the wide array of potential applications, more than 1200 different spark plug designs are available.

Because multi-cylinder passenger-car engines require at least one plug per cylinder, it is in this sector that most spark plugs are used.

Motorized machinery, because of the lower engine power, usually relies on a single-cylinder engine needing only a single spark plug.

Within Europe, most commercial vehicles – at least in heavy-duty applications – are powered by diesel engines, which limits the demand for spark plugs in this segment. In the US, however, gasoline engines are also the most prevalent powerplants in heavy vehicles.

Variety of types

The engine of 1902 delivered only about 6 HP for each 1000 cc of displacement. Today's comparable figure is 100 HP, with up to 300 HP available from racing engines. The technical resources invested in engineering and producing the spark plugs that allow this performance is enormous.

The first spark plug was expected to ignite 15 to 25 times per second. Today's spark plugs must ignite five times as often. The upper temperature limit as risen from 600 °C to approximately 900 °C, and the ignition voltage from 10,000 V to up to 30,000 V. Whereas today's spark plugs must function for at least 30,000 km, original spark plugs had to be replaced every 1000 km.

Although the spark plug's basic concept has changed little in the course of 100 years, in this period Bosch has designed more than 20,000 different types to meet the needs of various engine configurations.

The current spark-plug range continues to embrace a wide array of models. The spark plug is subject to immense demands in the areas of

- electrical and
- mechanical performance, as well as
- resistance to chemical and
- thermal loads.

In addition to satisfying these performance criteria, the spark plug must also be matched to the geometrical conditions defined by the individual engine (e.g, spark-plug length in the cylinder head). Combined with the extensive range of engines being manufactured, these requirements make it necessary to offer a wide variety of spark plugs. Bosch currently supplies more than 1250 different spark-plug types, all of which must be available to service workshops/garages and commercial distributors.

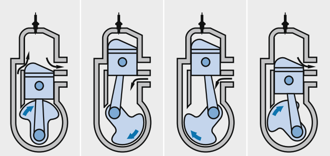
Requirements

Electrical-performance requirements

During operation in electronic ignition systems, spark plugs must handle voltages as high as 30,000 V with no disruptive discharge at insulator. Residue from the combustion process, such as soot, carbon and ash from fuel and oil additives, can be electrically conductive under certain thermal conditions. Yet under these same conditions it remains imperative that flashover through the insulator be avoided.

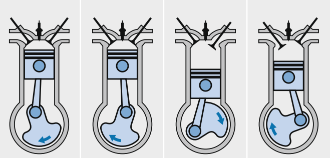
1 Temperature and pressure stresses on spark plugs

Two-stroke engine

Cycle phase	Bypass flow	Com-pression	Combustion and work	Exhaust
Gas temp.	...120 °C	200...400 °C	2000...2800 °C	500...1200 °C
Gas pressure	1 bar	5...8 bar	15...30 bar	1...3 bar
Piston position				

Crankshaft angle: 0° BDC – 90° – 180° TDC – 270° – 360° BDC

Four-stroke engine

Cycle phase	Com-pression	Combustion and work	Exhaust	Intake
Gas temp.	300...600 °C	2000...3000 °C	1300...1600 °C	...120 °C
Gas pressure	8...15 bar	30...50 bar	1...5 bar	0.9 bar
Piston position				

Crankshaft angle: 0° TDC – 180° BDC – 360° TDC – 540° BDC – 720° TDC

UMZ0325E

The insulator must continue to display adequate electrical resistance at up to 1000 °C with only very minor diminution of this figure throughout its service life.

Mechanical-performance requirements

The spark plug must be capable of withstanding periodic pressure peaks (up to about 100 bar) in the combustion chamber, while still providing an effective gas seal. High resistance to mechanical stresses is also required from the ceramic insulator, which is exposed to loads during installation as well as from the spark-plug connector and the ignition cable itself during operation. The shell must absorb the torque applied during installation with no permanent deformation.

Chemical-performance requirements

Because the spark plug extends into a combustion chamber hot enough to make its nose glow red, it is exposed to the chemical reactions that occur at extreme temperatures. Substances within the fuel can form aggressive residue deposits on the spark plug, affecting its performance characteristics.

Thermal-performance requirements

In operation the spark plug must alternately absorb heat from hot combustion gases and then withstand the cold incoming air/fuel mixtures in rapid succession. This is why insulators must display immense resistance to thermal shock.

The spark plug must also dissipate the heat absorbed in the combustion chamber to the engine's cylinder head with maximum efficiency; the terminal end of the spark plug should remain as cool as possible.

Design

The essential components of the spark plug are (Fig. 1)
- Terminal stud (1)
- Insulator (2)
- Shell (3)
- Seal seat (6), and
- Electrodes (8, 9)

Terminal stud
The steel terminal stud is mounted gas-tight in the insulator with an electrically conductive glass seal, which also establishes the connection to the center electrode. The terminal end protruding from the insulator features a thread for connecting the spark-plug connector of the ignition cable. In the case of connectors designed to ISO/DIN standards, a terminal nut (with the required outer contour) is screwed onto the terminal-stud thread, or the stud is equipped with a solid ISO/DIN connection manufacture.

Insulator
The insulator is cast in a special ceramic material. Its function is to insulate the center electrode and terminal stud from the shell. The demand for a combination of good thermal conductivity and effective electrical insulation is in stark contrast to the properties displayed by most insulating substances. Bosch uses aluminum oxide (Al_2O_3) along with minute quantities of other substances. Following firing, this special ceramic meets all requirements for mechanical and chemical durability, while its dense microstructure provides high resistance to disruptive discharge.

On air-gap spark plugs, the outer contour of the insulator nose can also be modified to improve heating for better response during repeated cold starts.

The surface of the insulator's terminal end is coated with a lead-free glaze. The glazing helps prevent moisture and contamination from adhering to the surface, which helps to prevent tracking currents to a large extent.

1 Spark plug design

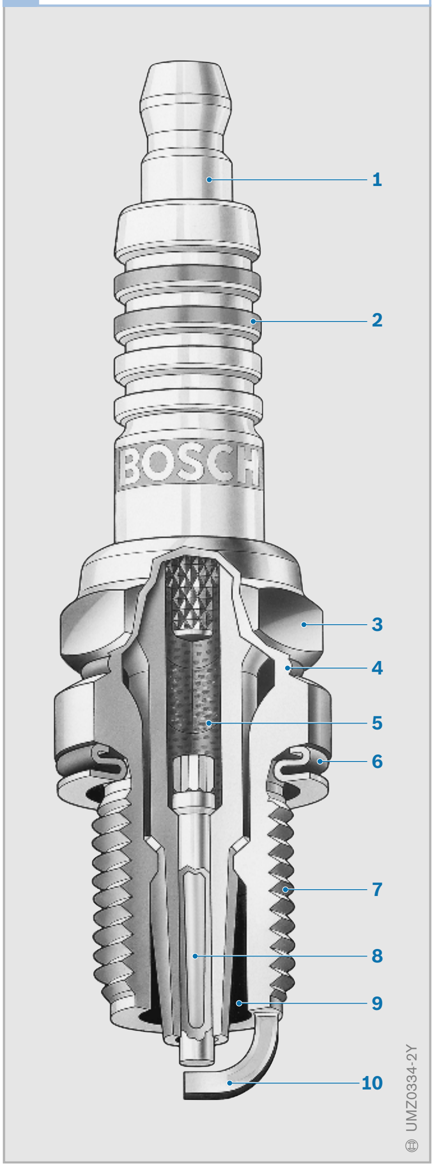


Fig. 1
1 Terminal stud with nut
2 Al_2O_3 ceramic insulator
3 Shell
4 Heat-shrinkage zone
5 Conductive glass
6 Sealing ring (seal seat)
7 Thread
8 Composite center electrode (Ni/Cu)
9 Breathing space (air space)
10 Ground electrode (here Ni/Cu composite)

Shell

The shell is manufactured from steel in a cold-forming process. The shell castings emerge from the pressing tool with their final contours, limiting subsequent machining operations to just a few areas.

2 Spark-plug seal seat

Fig. 2
a Flat seal seat with sealing ring
b Conical seal seat without sealing ring

1 Sealing ring
2 Conical sealing surface

The bottom end of the shell includes threads (Fig. 1, Pos. 7), making it possible to install the plug in the cylinder head and then remove it after a specified replacement interval. Depending on the specific design, as many as four ground electrodes can be welded to the end of the shell.

An electroplated nickel coating is applied to the surface to protect the shell against corrosion and prevent it from seizing in the sockets of the aluminum cylinder heads.

To accommodate the spark plug-wrench, the upper section of the conventional shell has a 6-point socket fitting; newer shell designs may use a 12-point fitting. The 12-point fitting makes it possible to reduce the socket attachment's size to 14 mm without modifying insulator-head geometry. This reduces the spark plug's space demands in the cylinder head and allows the engine designer greater freedom in locating the cooling passages.

The top end of the spark-plug shell is flanged after the plug core (comprising insulator with reliably mounted center electrode and terminal stud) has been inserted, and secures the plug core in position. The subsequent shrink-fitting process – inductive heating under high pressure – produces a gas-tight connection between insulator and shell to ensure effective thermal conductivity.

Seal seat

Depending on engine design, either a flat or conical seal seat (Fig. 2) effects the seal between the spark plug and the cylinder head.

In the case of a flat seal seat, a sealing ring (1) is used as the sealing element. This captive sealing ring is permanently attached to the spark-plug shell. Its special contours adapt to form a durable yet flexible seal when the spark plug is installed. In the case of a conical seal seat, a conical, or tapered, surface (2) on the spark-plug shell mates directly with the cylinder head to provide a seal without the use of a sealing ring.

Electrodes

During flashover and high-temperature operation, the electrode material is subjected to such strong thermal load that the electrodes become worn – the electrode gap widens accordingly. To satisfy demands for extended replacement intervals, electrode materials must effectively resist erosion (burning by the spark) and corrosion (wear due to aggressive thermochemical processes). These properties are achieved primarily through the use of temperature-resistant nickel alloys.

Center electrode

The center electrode (Fig. 1, Pos. 8), which includes a copper core for improved heat dissipation, is anchored at one end in the conductive glass seal.

In “long-life” spark plugs, the center electrode serves as the base material for a noble-metal pin, which is permanently connected to the base electrode by means of laser welding. Other spark plug designs rely on electrodes formed from a single thin platinum wire, which is then sintered to the ceramic base for good thermal conductivity.

Ground electrodes

The ground electrodes (10) are attached to the shell and usually have quadrilateral cross-sections. Available arrangements include the front electrode and the side electrode (Fig. 3b). The ground electrode’s fatigue strength is determined by its thermal conductivity. As with center electrodes, composite materials can be used to improve heat dissipation, but it is the length and the end surface that will ultimately determine the ground electrode’s temperature, and thus its resistance to wear.

Spark-plug life can be extended through the use of greater end-surface areas and multiple ground electrodes.

3 Electrode shapes

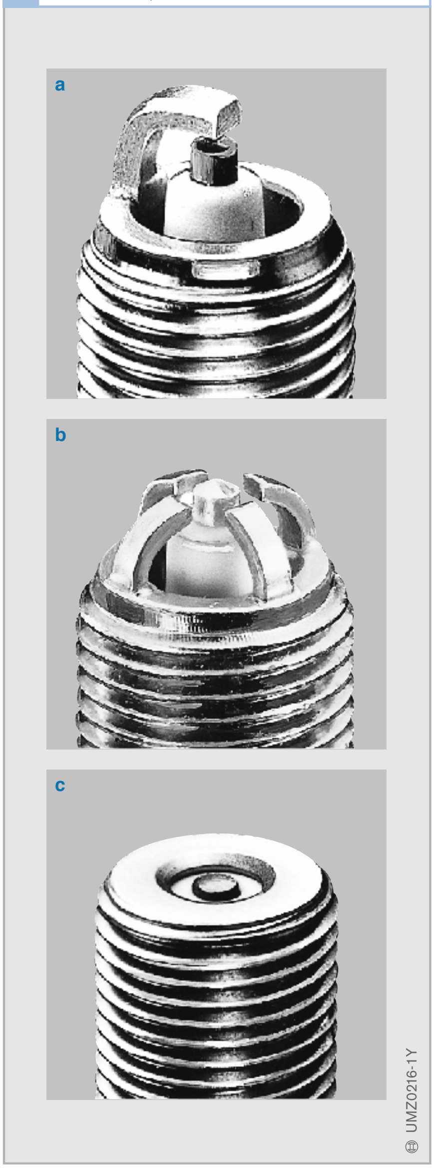


Fig. 3
- a Front electrode
- b Side electrodes
- c Surface-gap spark plug without ground electrode (special application for racing engines)

Electrode materials

As a basic rule, pure metals conduct heat better than alloys. Yet pure metals – such as nickel – are also more sensitive than alloys to chemical attack from combustion gases and solid combustion residues. Manganese and silicon can be added to nickel to produce alloys with enhanced resistance to aggressive chemical, especially sulfur dioxide (SO_2, sulfur is a constituent of lube oil and fuel). Aluminum and yttrium additives enhance resistance to scaling and oxidation.

Compound electrodes

Corrosion-resistant nickel alloys are now the most widely used option in spark-plug manufacture. A copper core can be used for further increases in heat dissipation, producing compound electrodes that satisfy exacting demands for high thermal conductivity and high corrosion resistance (Fig. 1).

The ground electrodes, which must be flexible enough to bend when the gap is set, may also be manufactured from a nickel-based alloy or from a composite material.

Silver-center electrodes

Silver has the best electrical and thermal conductivity of any material. It also displays extreme resistance to chemical attack, provided that it is not exposed to either leaded fuels or to high temperatures in reducing atmospheres (rich air/fuel mixture).

Composite particulate materials with silver as their basic substance can substantially enhance heat resistance.

Platinum electrodes

Platinum (Pt) and platinum alloys display high levels of resistance to corrosion, oxidation and thermal erosion. This is why platinum is the substance of choice for use in "long-life" spark plugs.

In some spark-plug types, the Pt pin is cast in the ceramic body early in the manufacturing process. In the subsequent sintering process, the ceramic material shrinks onto the Pt pin to permanently locate it in the plug core.

In other spark-plug types, thin Pt pins are welded onto the center electrode (Fig. 2). Bosch relies on continuous-operation lasers to produce a durable bond.

1 Spark plugs with compound electrodes

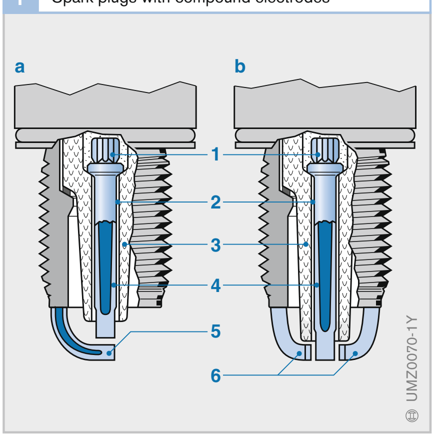


Fig. 1
a With front electrode
b With side electrode

1 Conductive glass
2 Air gap
3 Insulator nose
4 Composite center electrode
5 Composite ground electrode
6 Ground electrodes

2 Laser-welded pins

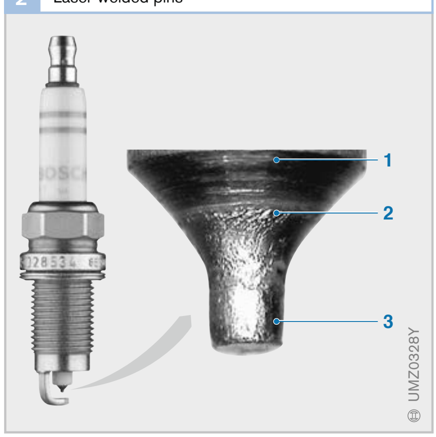


Fig. 2
1 Compound electrode (Ni/Cu)
2 Laser-welded seam
3 Platinum pin

Spark-plug concepts

The mutual arrangement of the electrodes and the locations of the ground electrodes relative to the insulator determine the type of spark-plug concept (Fig. 1).

Air-gap concept

Center and ground electrodes are configured to produce a linear spark to ignite the air-fuel mixture located within the space between them.

Surface-gap concept

As a result of the defined position of the ground electrodes relative to the ceramic, the spark travels initially from the center electrode across the surface of the insulator nose before jumping across a gas-filled gap to the ground electrode. Because the ignition voltage required to produce discharge across the surface is less than that needed to produce discharge across an air gap of equal dimensions, a surface-gap spark can bridge wider electrode gaps than an air-gap spark with an identical ignition-voltage demand. This produces a larger flame core for more effective creation of a stable flame front.

The surface-gap spark also promotes self-cleaning during repeated cold starts, preventing soot deposits from forming on the insulator nose. This improves performance on engines exposed to frequent cold starts at low temperatures.

Surface-air-gap concepts

On these spark plugs, the ground electrodes are arranged at a specific distance from the center electrode and the end of the ceramic insulator. This produces two alternate spark paths, which facilitate both forms of discharge – air gap and surface-air gap – and different ignition-voltage-demand values. Depending on operating conditions and spark-plug condition (wear), the spark travels as an air-gap or surface-air-gap spark.

1 Spark-plug concepts

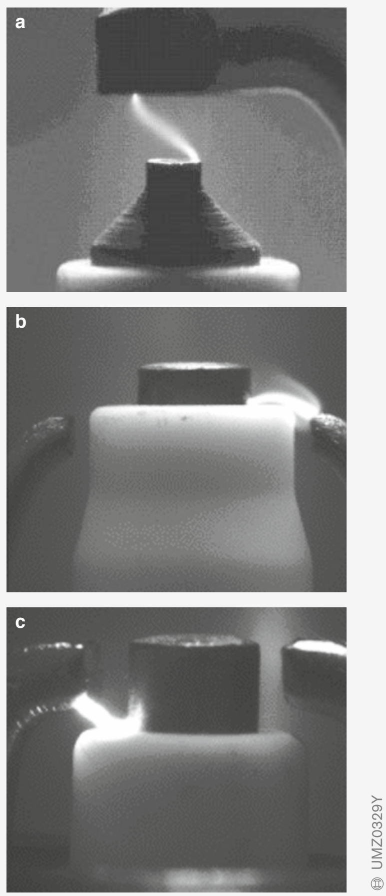


Fig. 1
a Air-gap spark
b Surface-gap spark
c Surface-air-gap spark

Electrode gap

As the shortest distance between the center and ground electrodes, the electrode gap determines, among others, the length of the spark (Fig. 1). The smaller the electrode gap, the lower the voltage that is required to generate an ignition spark.

An excessively small gap produces only a small flame core in the electrode area. Because this flame core loses energy through the electrode contact surfaces (quenching), the rate at which the flame core propagates is only very slow. Under extreme conditions, the energy loss can be high enough to produce ignition miss.

As electrode gaps increase (e.g., due to electrode wear), lower quenching losses lead to improved conditions for ignition, but larger gaps also increase the ignition-voltage demand (Fig. 2). The reserves afforded by any given level of ignition voltage in the ignition coil are reduced and the danger of ignition miss increases.

Engine manufacturers use various test procedures to determine the ideal electrode gap for each engine. The first step is to conduct ignition tests at characteristic engine operating points to determine the minimum electrode gap. Salient considerations include exhaust emissions, smooth operation and fuel consumption.

In subsequent extended test runs, the wear performance of these spark plugs is determined and then evaluated with regard to ignition-voltage demand. The specified electrode gap is then defined at a point providing an adequate safety margin to the miss limit. Gap specifications are quoted in vehicle owner's manuals as well as in Bosch spark-plug sales documentation.

Bosch spark plugs are set to the correct electrode gap at the factory.

1 Electrode gap

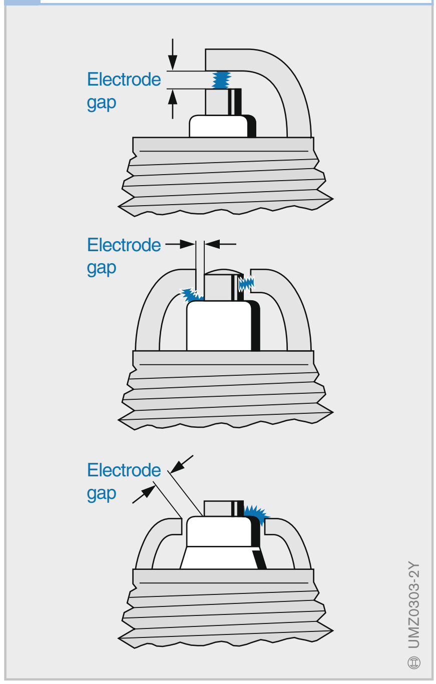


Fig. 1
- a Spark plug with front electrode (air-gap spark)
- b Spark plug with side electrode (air-gap or surface-air-gap spark)
- c Surface-gap spark plug

2 Relationship between electrode gap and ignition voltage

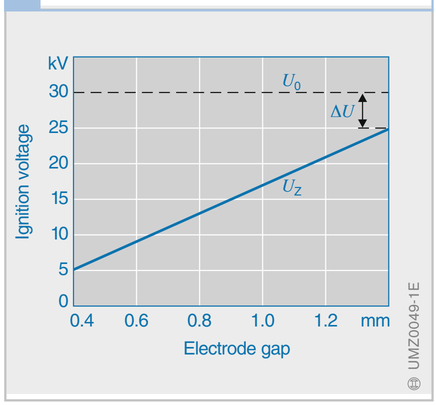


Fig. 2
- U_0 Available ignition voltage
- U_Z Ignition voltage
- ΔU Ignition-voltage reserve

Spark position

The spark position (Fig. 1a) is the location of the spark gap relative to the walls of the combustion chamber. Spark position has a substantial effect on combustion in modern engines (especially direct-injection engines). The criterion for defining the quality of the combustion process is the engine's operating consistency, or smoothness, which is in turn based on a statistical evaluation of the indicated mean effective pressure. The extent of the standard deviation or of the variation coefficient ($cov = s/p_{ime} \cdot 100$ [%]) is an index of the uniformity of the combustion. These values also provide information on any major effects that delayed or missed combustion will have on engine operation. A value of 5 % is defined for *cov* as the measure of the operation limit.

Figure 1 illustrates the effects of leaning out the air/fuel mixture and varying ignition timing on operational consistency at two different spark-plug positions. The lines describe constant consistency levels, while the 5 % limit is shown in bold blue. Values above this curve (< 5 % range) correlate with smooth engine operation – the combustion process of the individual working cycles is uniform and free from major fluctuations. Values below this curve (> 5 % range) correspond to poor engine operation – combustion is not always uniform, with isolated misses or delayed combustion occurring in extreme situations.

Comparison of the two diagrams indicates that on this engine projecting the spark position further into the combustion chamber would substantially improve ignition, as the ignition-timing range increases above the 5 % curve and the operating limit is pushed toward higher excess-air factors.

However, extending the length of the ground electrodes leads to higher temperatures, which in turn produce rises in electrode wear. The self-resonant frequency also falls, which can lead to ruptures and fissures from vibration. When the spark position is shifted forward, a number of other measures are needed to ensure adequate service life:

- Extending the spark-plug shell inward beyond the combustion-chamber wall. The shoulder reduces the danger of electrode rupture.
- Inserting copper cores into the ground electrodes. Placing copper in direct contact with the spark-plug shell can reduce temperatures by approximately. 70 °C.
- Using highly heat-resistant electrode materials.

1 Uneven running for different spark positions (*f*)

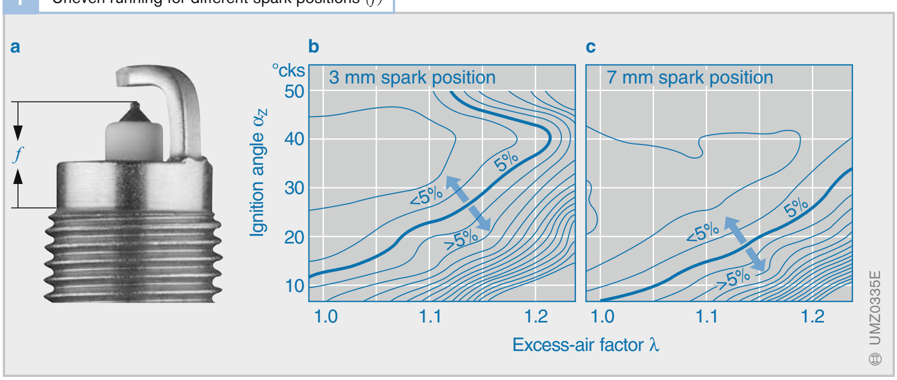


Fig. 1
a Definition of spark position *f*
b Diagram for *f* = 3 mm
c Diagram for *f* = 7 mm

Curves indicate operating points with constant *cov* values

$cov = s/p_{ime} \cdot 100$ [%]
s Standard deviation
p_{ime} Indicated mean effective pressure

5 % curve: operation limit
< 5 % range: good running consistency
> 5 % range: poor running consistency

Spark-plug heat range

Spark-plug operating temperatures

Operating range

Engines run on a rich air/fuel mixture when cold. This can lead to incomplete combustion and formation of soot deposits on spark plugs and combustion-chamber surfaces. These deposits contaminate the insulator nose to form a partially conductive link between the center electrode and the spark-plug shell (Fig. 1). This "shunting" effect allows a portion of the ignition energy to escape as "shunt current", reducing the overall energy available for ignition. As contamination increases, so does the probability that no spark will be produced.

The tendency for combustion residues to form deposits on the insulator nose is heavily dependent on its temperature and takes place predominantly at temperatures below approximately. 500 °C. At higher temperatures, the carbon-based residues are burned from the insulator nose, i.e., the spark plug cleans itself.

The objective is therefore to heat the insulator nose to an operating temperature which is above the "self-cleaning limit" of roughly 500 °C (for unleaded fuel) and is obtained shortly after starting.

An upper temperature limit of approximately 900 °C should not be exceeded. Above this limit, the electrodes are subject to heavy wear due to oxidation and hot-gas corrosion.

If temperatures rise even further, the risk of auto-ignition can no longer be ruled out (Fig. 2). In this process, the air/fuel mixture ignites on the hot spark-plug components to produce uncontrolled ignition events; these can damage or even destroy the engine.

Thermal loading capacity

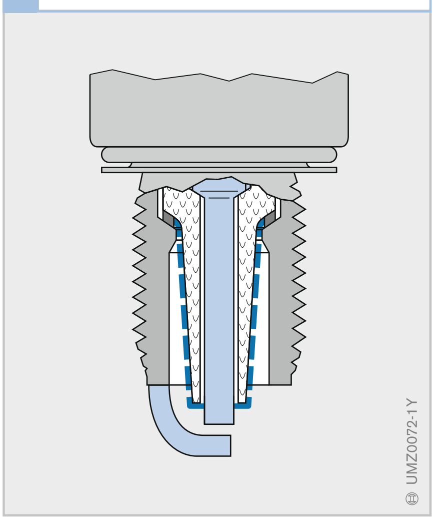
When the engine is running, the spark plug is heated by the temperatures generated in the combustion process. Some of the heat absorbed by the spark plug is dissipated to the fresh gas. Most is conducted via the center electrode and the insulator to the spark-plug shell, from which point it is dissipated to the cylinder head (Fig. 3). The ultimate

Fig. 1
- - - Shunt current

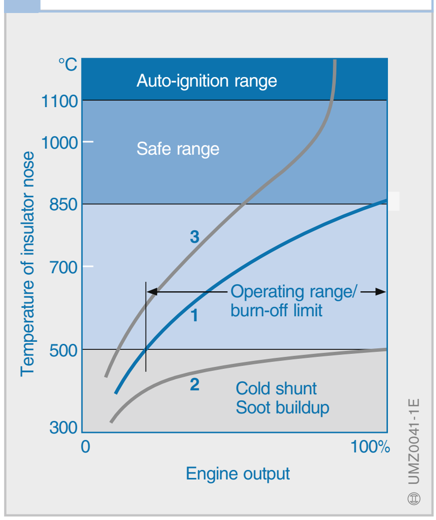
Fig. 2
1 Spark plug with correct heat-range code number
2 Spark plug with heat-range code number too low (cold plug)
3 Spark plug with heat-range code number too high (hot plug)

The temperature in the operating range should be 500...900 °C at the insulator, varying according to engine power

1 Current shunt on a contaminated insulator nose reduces the available high voltage



2 Spark-plug operating range



operating temperature is the point at which absorption of heat from the engine and its dissipation to the cylinder head reach a state of equilibrium.

The amount of heat supplied is dependent on the engine. Engines with high specific power output generally operate with higher combustion-chamber temperatures than those with low specific power output.

The design of the insulator nose is the primary determinant of heat dissipation. The size of the insulator surface determines heat absorption, while the cross-sectional area and the center electrode affect heat dissipation.

The spark plug's heat-absorption capacity must therefore be matched to the individual engine type. The index indicating a spark plug's thermal loading capacity is its heat range.

Heat range and heat-range code number

The heat range of a spark plug is determined relative to calibration spark plugs and described with the aid of a heat-range code number. A low code number (e.g., 2...5) indicates a "cold" spark plug with low heat absorption through a short insulator nose. A high code number (e.g., 7...10) indicates a "hot" spark plugs with high heat absorption through a long insulator nose. These code numbers form an integral part of the spark-plug designation so that spark plugs with different heat ranges can be easily distinguished and allocated to different engines.

The correct heat range is determined in full-load measurements because it is at these very operating points that thermal loading of spark plugs is at its greatest. During operation, the spark plugs should never become so hot as to represent a source of thermal auto-ignition. The heat-range recommendation is always defined with a safety margin relative to this auto-ignition limit to accommodate production variations in both plugs and engines. This margin is also important in view of the fact that an engine's thermal properties can vary over the course of time. One example is the potential increase in compression ratio caused by ash deposits in the combustion chamber, which in turn results in higher temperatures for the spark plug. If no malfunctions occur with sooted spark plugs in the subsequent cold-starting tests with this heat-range recommendation, then the correct heat range for the engine is determined.

Because vehicle engines display a wide range of different properties with regard to operating loads, method of operation, compression, engine speed, cooling and fuel, it is impossible to use just one spark plug for all engines. A plug that overheats in one engine would run at relatively cold temperatures in another.

3 Thermal conduction paths in the spark plug

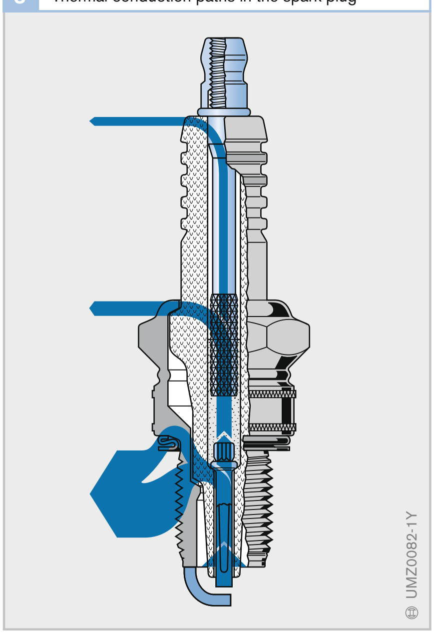


Fig. 3
A large proportion of the heat absorbed from the combustion chamber is dissipated by thermal conduction (small contribution to cooling of approximately 20 % from flow of fresh induction mixture is not included)

Adaptation of spark plugs

Bosch works together with engine manufacturers in jointly defining the ideal spark plugs for each engine.

Temperature measurement

Thermocouple spark plugs specially designed and produced for temperature monitoring (Fig. 1) provide initial information on the right choice of plug. A thermocouple (2) embedded in the center electrode (3) makes it possible to record the temperatures in the individual cylinders as a function of engine speed and load. This process represents a simple means of identifying the hottest cylinder and operating conditions for subsequent measurements as well as assisting in reliable designation of the correct plug for any specific application.

1 Thermocouple spark plug

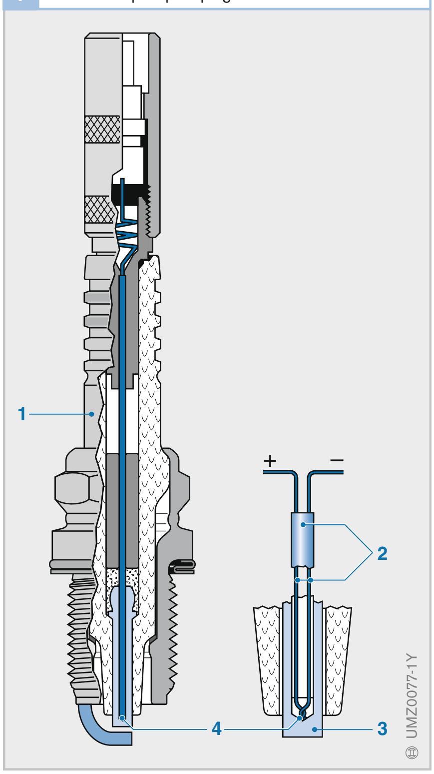


Fig. 1
1 Insulator
2 Thermocouple sleeve
3 Center electrode
4 Measuring point

Ionic-current measurement

The Bosch ionic-current measurement procedure employs the combustion process as a factor for determining the heat-range requirement. The ionizing effect of flames enables the progress in terms of time of combustion to be assessed by measuring the conductivity in the spark gap (Fig. 2). Because the electrical ignition spark produces a large number of charged particles in the spark gap, the ionic current rises sharply at the moment of ignition. Although the current flow falls once the ignition coil is discharged, the number of charged particles maintained by the combustion process is large enough to allow continued monitoring. Simultaneous monitoring of combustion-chamber pressure provides a record of normal combustion with a uniform pressure increase, peaking after ignition TDC. If the spark plug's heat range is varied during these measurements, the combustion process displays characteristic shifts with the thermal loading of a spark plug as a function of the heat range (Fig. 4).

2 Schematic diagram of ionic-current measurement

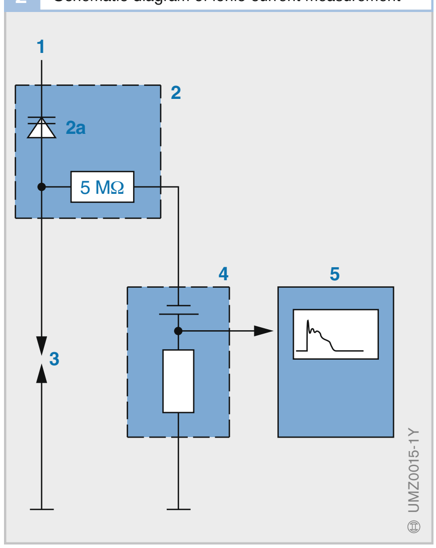


Fig. 2
1 High voltage from ignition coil
2 Ionic-current adapter
2a Break-over diode
3 Spark plug
4 Ionic-current device
5 Oscilloscope

The advantage of this method over measurements focusing exclusively on temperatures in the combustion chamber is that it indicates ignition probability, which is dependent not only on temperature, but also on the design parameters of the engine and the spark plug.

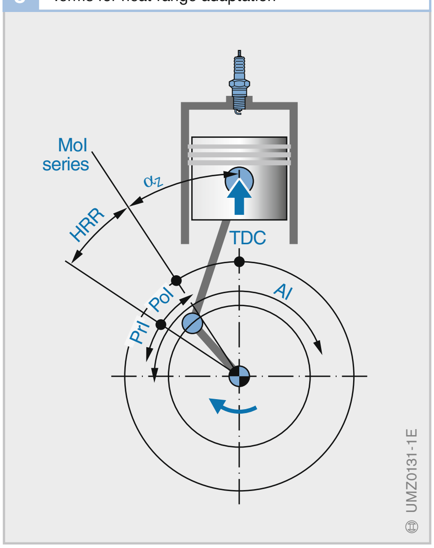
Definition of terminology

Terminology and definitions for uncontrolled ignition of air/fuel mixtures for heat-range adaptation of spark plugs have been defined in an international agreement (ISO 2542 – 1972, Fig. 3).

Thermal auto-ignition

Auto-ignition is defined as a process that results in ignition of the air/fuel mixture without an ignition spark, usually starting on a hot surface (e.g., on the excessively hot insulator-nose surface of a spark plug with too high a heat range). These events can be classified in one of two categories, according to the point at which they occur relative to the moment of ignition.

3 Terms for heat-range adaptation



4 Characteristic ionic-current oscillograms

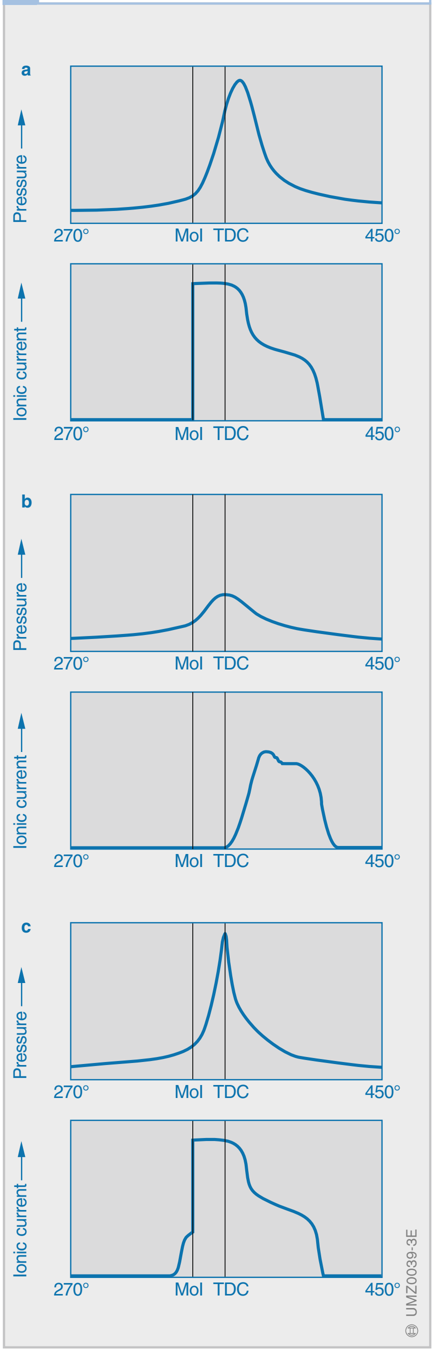


Fig. 3
AI Auto-Ignition
TDC Top Dead Center
PrI Pre-Ignition
PoI Post-Ignition
HRR Heat-Range Reserve in °cks
MoI Moment of Ignition in °cks before TDC
α_Z Ignition angle

Fig. 4
a Normal combustion
b Scanned ignition with post-ignition
c Pre-ignition

Post-ignition
Post-ignition occurs after the moment of electrical ignition, but is not a critical factor in practical engine operation in that electrical ignition always takes place earlier. Conducting measurements to determine whether the spark plug is producing thermal auto-ignition entails suppressing the electrical spark. When post-ignition occurs, the sharp rise in ionic current does not occur until after the moment of ignition. But, because it initiates a combustion process, a pressure rise and therefore a torque output are also registered (Fig. 4b).

Pre-ignition
Pre-ignition occurs before the moment of electrical ignition (Fig. 4c) and can cause serious engine damage due to its uncontrolled progression. Premature initiation of the combustion process shifts the pressure peak relative to TDC while also increasing maximum pressure levels in the combustion chamber, promoting additional thermal load on the components in the combustion chamber. It is thus essential when adapting spark plugs to ensure that no pre-ignition will take place.

Assessment of measurement results

The Bosch ionic-current measurement procedure can be used to detect both types. However, the ignition spark must be suppressed at specific intervals for the purpose of detecting post-ignition. The point at which post-ignition occurs relative to the moment of ignition combines with the percentage of post-ignition events relative to the scan rate to provide information on the stresses to which the spark plug is being subjected within the engine. Because spark plugs with extended insulator noses (hot spark plugs) absorb more heat from the combustion chamber and dissipate that heat less effectively, they are more likely to induce post-ignition or even pre-ignition than spark plugs with shorter insulator noses. The application measurements employed to select the correct heat range for the respective engine thus rely on mutual comparisons of spark plugs with various heat ranges and analysis of their tendency to produce pre-ignition or post-ignition.

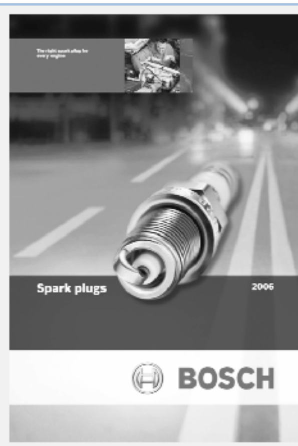
The preferred environments for conducting spark-plug adaptation measurements are thus the engine test stand and the chassis dynamometer. For reasons of safety, measurement test runs to determine the hottest operating point at full load over an extended period of time on public highways are not permitted.

Spark-plug selection

The object of an adaptation is to select a spark plug which can be operated without pre-ignition and which has an adequate heat-range reserve, i.e., pre-ignition should not occur with spark plugs that are not hotter by at least two heat-range numbers.

As this section has indicated, selection and use of spark plugs is a finely-tuned process. The procedure for choosing the ideal spark plug generally includes close cooperation between the spark-plug manufacturer and the engine manufacturer.

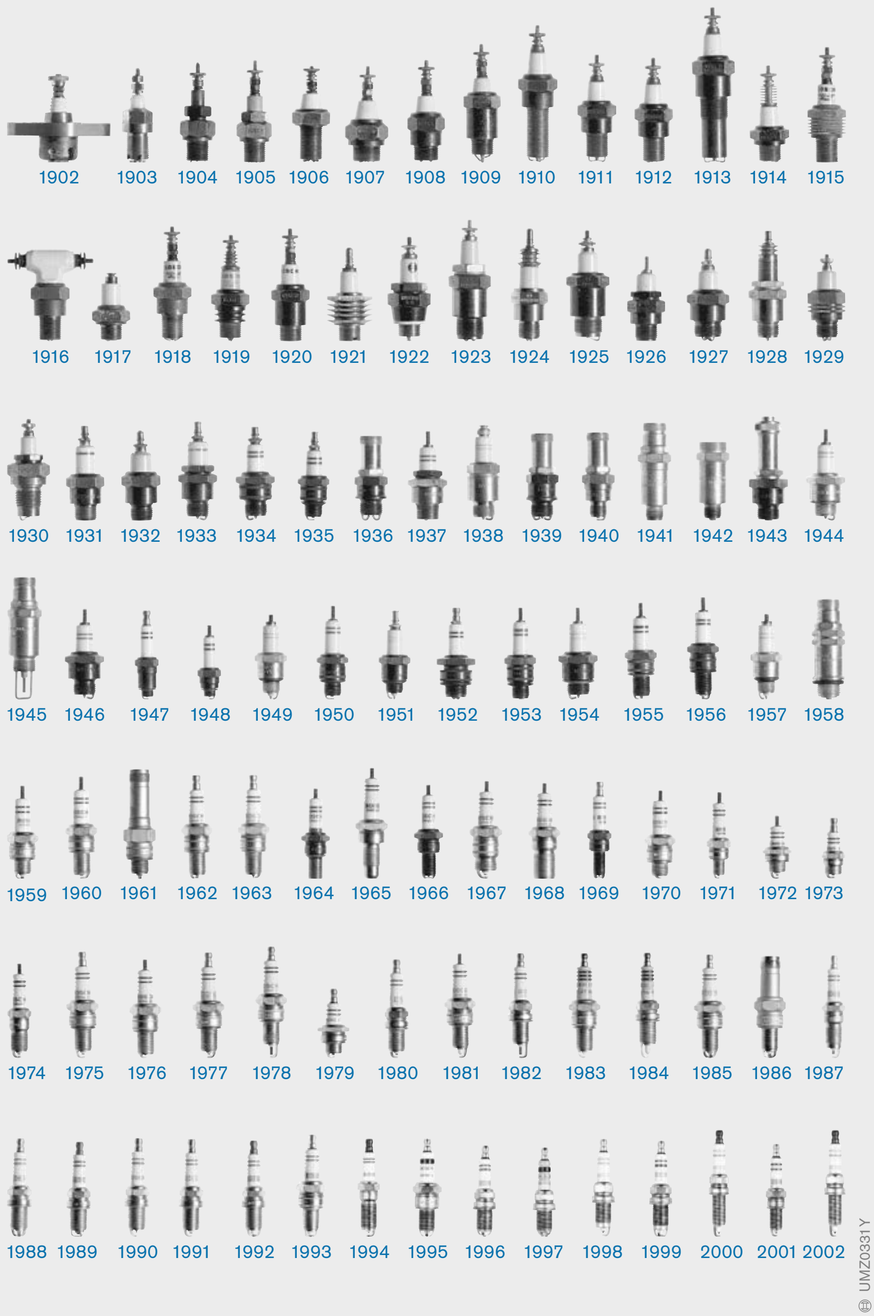
5 Bosch Spark-Plug Catalog



SMZ0354E

Fig. 5
Spark-plug selection:
The engine manufacturer's specifications and the recommendations contained in the Bosch sales documents are binding on drivers.
Bosch supplies the ideal spark plug for every engine –
You can find the right plug in this catalog

100 years of spark plugs – product variety



Spark-plug performance

Changes in the course of service life

Because spark plugs operate within an aggressive atmosphere, sometimes at extremely high temperatures, electrodes are subject to wear, which increases the ignition-voltage demand. When the situation finally reaches the point at which the ignition-voltage demand can no longer be covered by the ignition coil, then ignition misses occur.

Spark-plug operation can also be detrimentally affected by changes in an aging engine and by contamination. As engines age, blowby and leakage increase, raising the amount of oil in the combustion chamber. This, in turn, leads to more deposits of soot, ash and carbon on the spark plug, which can give rise to shunting, ignition misses, and in extreme cases auto-ignition. Yet another factor is the use of antiknock additives in fuels, which can form deposits, become conductive at high temperatures, and produce hot shunts. The ultimate result is ignition miss, characterized by a substantial increase in pollutant emissions along with potential damage to the catalytic converter. This is why spark plugs should be replaced at regular intervals.

1 Wear on center and ground electrodes

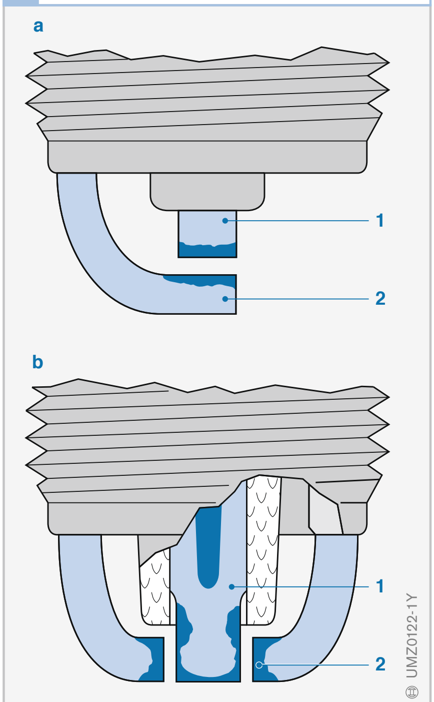


Fig. 1
a Spark plug with front electrode
b Spark plug with side electrodes

1 Center electrode
2 Ground electrode

Electrode wear

Electrode wear is synonymous with electrode erosion, a material loss which causes the gap to grow substantially over the course of time. This phenomenon essentially arises from two sources:

- Spark erosion, and
- Corrosion in the combustion chamber

Spark erosion and corrosion

Flashover of electrical sparks causes the electrodes to heat up to their melting point. The minute, microscopic particles deposited on surfaces react with the oxygen or the other constituents of the combustion gases. This results in material erosion, widening the electrode gap and raising the ignition-voltage demand (Fig. 1).

Electrode wear is minimized by using materials with high temperature stability (e.g., platinum and platinum alloys). It is also possible to reduce erosion without limiting service life using suitable electrode geometry (e.g., smaller diameter, thin pins) and alternate spark-plug designs (surface-gap plugs).

The electrical resistance effected in the conductive glass seal also reduces erosion and wear.

Abnormal operating states

Abnormal operating states can destroy both the spark plugs and the engine.
Such states include:

- Auto-ignition
- Combustion knock, and
- High oil consumption (ash and carbon deposits)

Engine and spark plugs can also be damaged by incorrect ignition-system settings, spark plugs with the wrong heat range for the engine, and unsuitable fuels.

Auto-ignition

Auto-ignition is an uncontrolled ignition process accompanied by increases in combustion-chamber temperatures severe enough to cause serious damage to both spark plugs and engine.

Full-load operation can produce localized hot spots and induce auto-ignition in the following areas:

- At the spark-plug's insulator nose
- On exhaust valves
- On protruding sections of cylinder-head gaskets, and
- On flaking deposits

Combustion knock

Knocking is characteristic of an uncontrolled combustion process with very sharp rises in pressure. Knock is caused by spontaneous ignition of the mixture in areas which the advancing flame front, initiated by the usual electrical spark, has not yet reached. Combustion proceeds at a considerably faster rate than normal. High-frequency pressure pulsations with extreme pressure peaks are then superimposed on the normal pressurization curve (Fig. 3). The severe pressure gradients expose components (cylinder head, valves, pistons and spark plugs) to extreme thermal loads capable of damaging one or numerous components.

The damage is similar to that associated with cavitation damage from ultrasonic flow currents. On the spark plug, pitting on the ground electrode's surface is the first sign of combustion knock.

2 Ground electrode damaged from excessive knock

3 Cylinder pressure curve

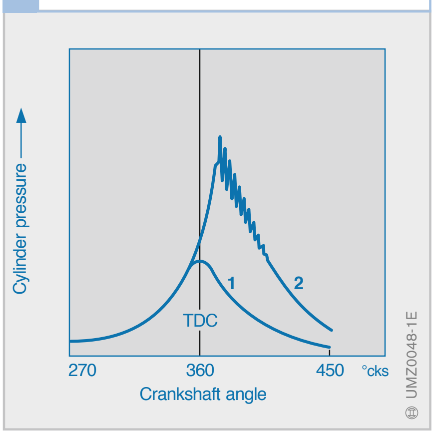


Fig. 3
1 Normal combustion
2 Combustion knock

Types

SUPER spark plug

SUPER spark plugs (Fig. 1) make up the majority of the Bosch spark-plug range, and serve as the basis for various derivative spark-plug types and concepts. A suitable version with precisely the right heat range is available for virtually every engine and application.

A cutaway view of the SUPER spark plug is shown in the section entitled "Design" (Fig. 1). The most significant characteristics of the SUPER spark plug are:

- A composite center electrode consisting of nickel-chromium alloy and featuring a copper core
- Optionally, a composite ground electrode for reducing ground-electrode wear by reducing the maximum temperature at the electrode, and
- An electrode gap that is preset for the relevant engine the factory

Various spark-plug profiles are employed to satisfy specific individual demands. The spark plug illustrated in Figure 2b is a current version that varies in a number of details from the classic SUPER (Fig. 2a). The spark position projects further into the combustion chamber, while optimized insulator-nose geometry and a thinner center electrode offer improved performance in repeated cold starts.

The version in Figure 2c features a laser-welded noble-metal pin. This not only extends service life, but also improves ignition and flame propagation thanks to its small diameter.

SUPER 4 spark plug

Design

The special features that distinguish the Bosch SUPER 4 spark plug from conventional SUPER plugs include

- Four symmetrically arranged ground electrodes (Fig. 3)
- A silver-plated center electrode, and
- A preset electrode gap requiring no adjustment during the plug's service life

1 The SUPER spark plug from Bosch

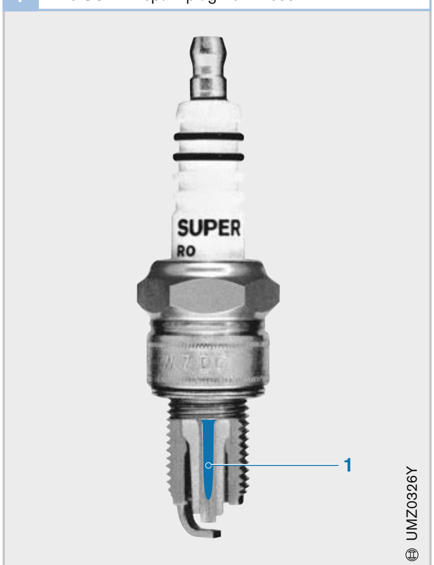


Fig. 1
1 Composite center electrode with copper core

2 SUPER spark plug electrode shapes

Fig. 2
a Front electrode
b Front electrode and forward spark
c Front electrode and platinum center electrode

Method of operation

The four ground electrodes are manufactured from a thin profile section to ensure good ignition and flame-front propagation. The defined gap separating them from the center electrode and the insulator nose allows the spark – depending on the operating conditions – to jump either as an air-gap spark or as a surface-air-gap spark. The result is a total of eight potential spark gaps. Which of these spark gaps is selected is dependent on the operating conditions and the density of the air/fuel mixture at the moment of ignition.

Uniform electrode wear

Because the probability of spark propagation is the same for all electrodes, the sparks are evenly distributed across the insulator nose. In this way, even the wear is evenly distributed across all four electrodes.

Operating range

The silver-plated center electrode provides effective heat dissipation. This reduces the risk of auto-ignition due to overheating and extends the safe operating range. These assets mean that each SUPER 4 has a heat range corresponding to at least two ranges in a conventional spark plug. In this way, a wide range of vehicles can be refitted during servicing with relatively few spark-plugs types.

Spark-plug efficiency

The SUPER 4's thin ground electrodes absorb less energy from the ignition spark than the electrodes on conventional spark plugs. The SUPER 4 thus offers higher operating efficiency by providing up to 40 % more energy to ignite the air/fuel mixture (Fig. 5).

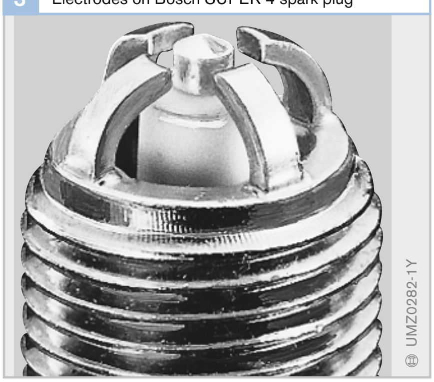
Ignition probability

Higher excess air (lean mixture, $\lambda > 1$) reduces the probability that the energy transferred to the gas will be sufficient to ignite the mixture reliably. In laboratory tests, the SUPER 4 has demonstrated the ability to ignite reliably mixtures as lean as $\lambda = 1.55$, whereas more than half of all ignition attempts failed under these conditions when a standard spark plug was used (Fig. 5).

Performance in repeated cold starts

Surface-gap sparking ensures effective self-cleaning, even at low temperatures. This means that up to three times as many cold starts (starting without warming up the engine) are possible as with conventional plugs.

3 Electrodes on Bosch SUPER 4 spark plug



4 Spark-plug efficiency

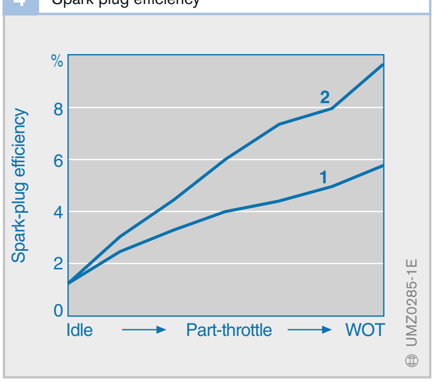


Fig. 4
1 Conventional spark plug
2 Bosch SUPER 4 spark plug

Environmental and catalytic-converter protection

Improved cold-start performance and more reliable ignition, under all conditions including the warm-up phase, reduce the amount of unburnt fuel and thereby the HC emissions.

Advantages

The improved properties that set the SUPER 4 apart from conventional spark plugs include:

- Greater ignition reliability thanks to eight potential spark gaps
- Self-cleaning thanks to surface-gap technology, and
- Extended heat range

Platinum+4 spark plug

Design

The Platinum+4 spark plug (Fig. 6) is a surface-gap spark plug designed for extended replacement intervals. It is distinguished from conventional spark plugs by

- Four symmetrically arranged ground electrodes with double curvatures (9)
- A thin sintered center electrode made from platinum (8)
- A geometrically improved contact pin (7) made from a special alloy
- A ceramic insulator (2) with high breakdown resistance, and
- An insulator nose redesigned for improved performance

5 Effect of mixture composition on ignition probability

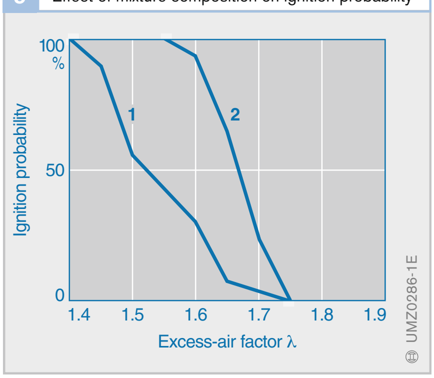


Fig. 5
1 Conventional spark plug
2 Bosch SUPER 4 spark plug

Method of operation

Ignition reliability

The extended electrode gap of 1.6 mm lends the Platinum+4 the capacity to deliver outstandingly reliable ignition, while the four earth electrodes assume an ideal position in the combustion chamber to ensure that the ignition spark has unobstructed access to the mixture. This allows the flame core to spread into the combustion chamber with virtually no interference, ensuring complete ignition of the entire air/fuel mixture.

6 Design of Platinum+4 spark plug

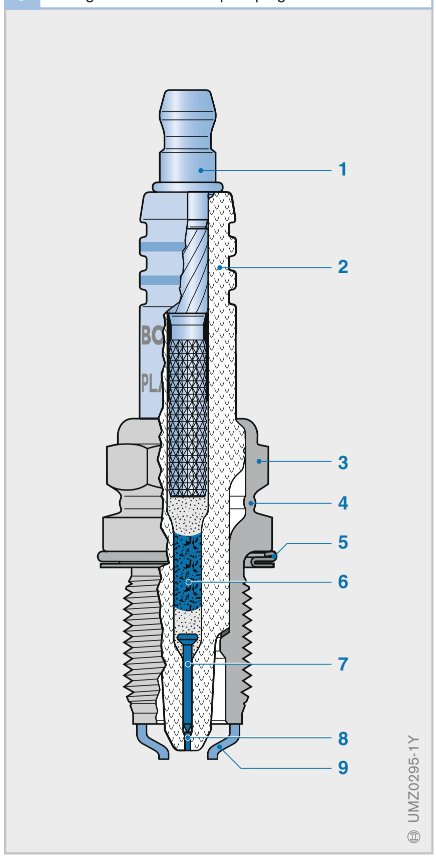


Fig. 6
1 Terminal stud
2 Insulator
3 Shell
4 Heat-shrinkage zone
5 Sealing ring
6 Conductive glass seal
7 Contact pin
8 Platinum pin (center electrode)
9 Ground electrodes (only two of four electrodes shown)

Response to repeated cold starts
The surface-gap concept provides substantial improvements over air-gap plugs in repeated cold starting.

Electrode wear
There are also advantages in respect of electrode wear, thanks to the erosion-resistant platinum pin in the center electrode and improved materials in the four ground electrodes. The resistance in the conductive glass seal reduces capacitive discharge, making a further contribution to reduced spark erosion.

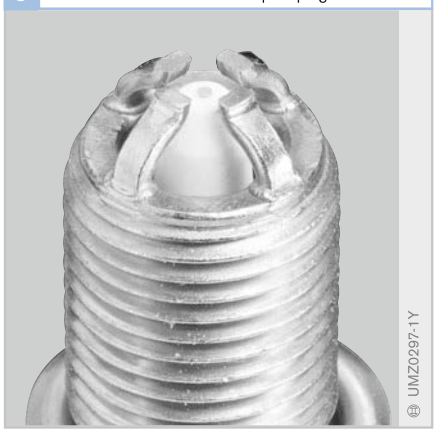
The comparison in Figure 7 shows the rise in demand for ignition energy over a period of engine operation of 800 hours on an engine test stand (corresponding to 100,000 km of highway use). The Platinum+4 spark plug's lower electrode wear delivers substantial reductions in the rate at which voltage demand increases relative to conventional spark plugs. Figures 8 and 9 show the profiles of a Platinum+4 spark plug when new and after a period of engine operation of 800 hours; the minimal electrode wear at the end of the endurance test is clear to see.

Advantages of the Platinum+4 spark plug

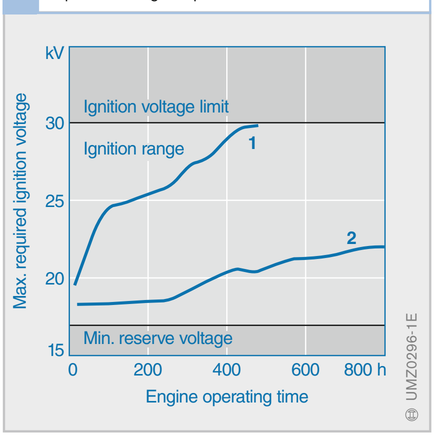
The Platinum+4 spark plug is characterized by a host of properties which make it ideal for extended-duty applications:

- Durable electrodes and ceramic components extend the plug-replacement intervals to up to 100,000 km
- Higher numbers of repeated cold starts possible
- Extremely good ignition and flame-front propagation for major improvements in smooth engine running

8 Profile of a new Platinum+4 spark plug



7 Increase in ignition-voltage demand during a period of engine operation



9 A Platinum+4 spark plug after 800 hours of operation

Fig. 7
1 Spark plug with air-gap spark (gap = 0.7 mm)
2 Platinum+4 spark plug with surface-gap spark (gap = 1.6 mm)

Spark plugs for direct-injection gasoline engines

In direct-injection engines, the fuel is introduced in stratified-charge mode via the high-pressure injector directly into the combustion chamber during the compression stroke. The design of the intake manifold and the piston crown generates a swirl- or tumble-like charge movement with which the fuel is transported to the spark plug. Because both the mass and direction of the flow vary at the engine's different operating points, a spark position projecting far into the combustion chamber is very advantageous to mixture ignition. This forward-spark concept has a negative effect on the temperature of the ground electrode to the extent that measures need to be take to reduce the temperature. By extending the shell into the combustion chamber, it is possible to reduce further the length of the ground electrode and thereby its temperature so that workable spark-plug concepts are possible.

Because of the numerous possible spark gaps, surface-gap concept offer a greater degree of reliability with regard to ignition misses. The improved self-cleaning performance by the surface-gap spark marks this spark-plug concept out for the wall- and air-guided combustion processes.

If the flow velocity at the spark location is not too great, even air-gap plugs can deliver good ignition results. This is because

- The spark is not so sharply deflected
- Breakaway and re-ignition are avoided, and
- The ignition energy can be transferred to generate a stable flame core

In the wall- and air-guided combustion processes, stratified mixture formation is closely linked to piston stroke to the extent that adjustment of combustion to the optimum efficiency cannot always be guaranteed. In addition, soot is caused by the intensive contact of the spray with the cylinder wall and the piston. For this reason, combustion processes which do not manifest these disadvantages have taken hold in recent years. By injecting the fuel during the induction stroke, the air/fuel mixture is set to $\lambda = 1$ and the engine is operated under homogeneous conditions. The homogeneous combustion processes place similar

10 Spark plugs for direct-injection gasoline engines

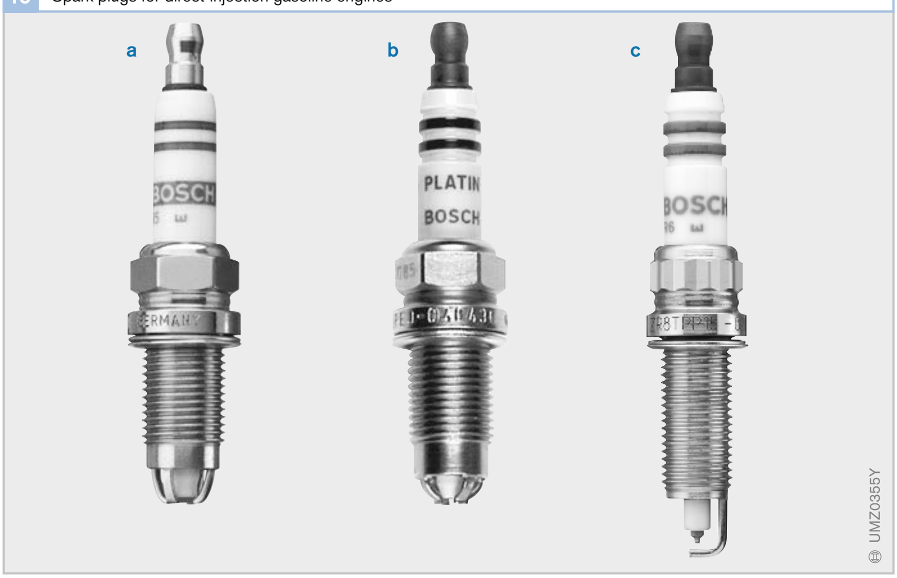


Fig. 10
- a Surface-gap spark plug without noble metal
- b Surface-gap spark plug with platinum center electrode
- c Air-gap spark plug with platinum on center electrode

demands on the ignition performance of the spark plugs, as is the case with manifold-injection engines. However, these engines are often operated with exhaust-gas turbochargers in order to achieve higher power figures, i.e., at the moment of ignition the air/fuel mixture has a higher density and therefore also a higher ignition-voltage demand. Here, air-gap plugs with noble-metal pins are generally used on the center electrode in order to be able to reliably satisfy the service-life requirements after 60,000 km and more.

Spray-guided combustion processes

In contrast, the demands placed on spark plugs are significantly greater in more recent developments pertaining to spray-guided combustion processes. Due to the fact that the spark plug is located close to the fuel injector, long, narrow plugs are preferred because this shape allows addition cooling passages to be accommodated between the injector and the spark plug. The alignment of the spark plug to the injector must be determined in extensive tests. In this way, the spark is drawn into the peripheral area of the spray by the flow of the injection jet (entrainment flows), and thereby ignition of the mixture is ensured.

In these combustion processes, it is extremely important for the spark always to jump at the same location. By configuring the geometry of the spark plugs on the combustion-chamber side, it possible to prevent the spark from disappearing in the breathing space (air space between the spark-plug shell and the insulator on the combustion-chamber side) so that it remains available for ignition. But reversing the ignition polarity (center electrode as the anode, ground electrode as the cathode) is another way of avoiding surface-gap sparking into the spark-plug shell (Fig. 11). It is also necessary to check whether restricted axial/radial position tolerances are needed in order to reduce the reciprocal action between the injector and the spark plug.

If the spark plug is situated too closely to the injector, the peripheral zone of the spray will not yet be sufficiently prepared such that ignition problems may arise due to over-rich mixture zones. If the spark plug is situated too far away from the injector, this may already give rise in the peripheral zones of the spray to leaning-out effects, which in turn are not conducive to a stable ignition phase.

In the case of a close spray-cone tolerance, it is also necessary to keep the spark location constant. If the spark position is too deep, the spark plug projects into the spray and is saturated with fuel; this may cause damage to the spark plug and sooting on the insulator. If the spark position is pulled back too far towards the combustion-chamber wall, the spray might no longer be drawn into the mixture by the spray-induced flow, resulting in ignition misses.

From this, it is possible to deduce that close coordination and cooperation is required between the design engineers responsible for spark-plug development and combustion-process in order to ensure reliable functioning in the spray-guided combustion processes.

11 Air-gap and surface-gap sparks in a spray-guided combustion process

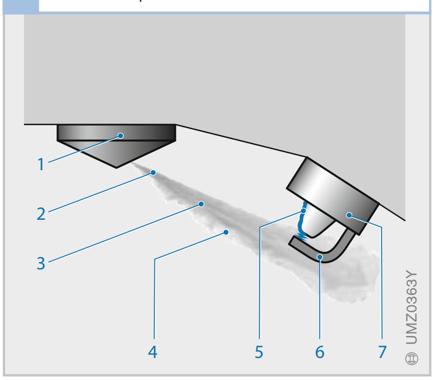


Fig. 11
The air-gap spark can ignite the air/fuel mixture, the surface-gap spark is generated outside the mixture cloud

1 High-pressure fuel injector
2 Fuel spray
3 Rich area
4 Lean area
5 Surface-gap spark
6 Air-gap spark
7 Spark plug

Special-purpose spark plugs

Applications

Special-purpose spark plugs are available for use in certain applications. These plugs feature unique designs dictated by the operating conditions and installation environments in individual engines.

Spark plugs for motor-sport applications

Constant full-load operation subjects the engines in competition vehicles to extreme thermal loads. The spark plugs produced for this operating environment usually have noble-metal electrodes (silver, platinum) and a short insulator nose. The heat absorption of these spark plugs is very low through the insulator nose, while heat dissipation through the center electrode is high (Fig. 12).

Spark plugs with resistors

A resistor can be installed in the supply line to the spark plug's spark gap to suppress transmission of interference pulses to the ignition cable and thereby educe interference radiation. The reduced current in the ignition spark's arcing phase also leads to lower electrode erosion. The resistor is formed by the special conductive glass seal between the center electrode and the terminal stud. Appropriate additives lend the conductive glass seal the desired level of resistance.

Fully-shielded spark plugs

Shielded spark plugs may be required in applications characterized by extreme demands in the area of interference suppression (radio equipment, car phones).

In fully shielded spark plugs, the insulator is surrounded by a metal shielding sleeve. The connection is inside the insulator. A union nut attaches the shielded ignition cable to the sleeve. Fully shielded spark plugs are also watertight (Fig. 13).

12 Competition spark plug

Fig. 12
1 Silver center electrode
2 Short insulator

13 Fully-shielded spark plug

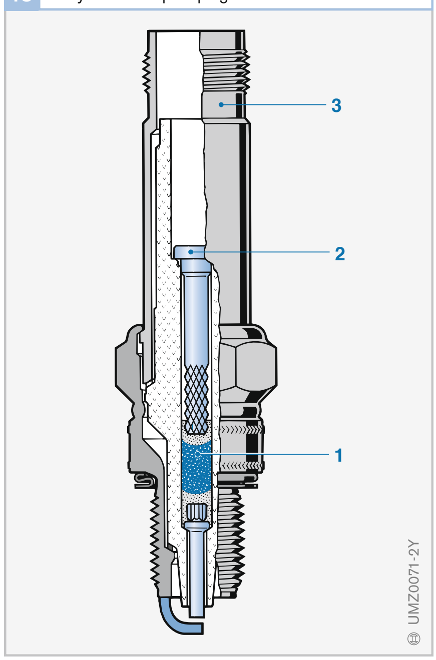
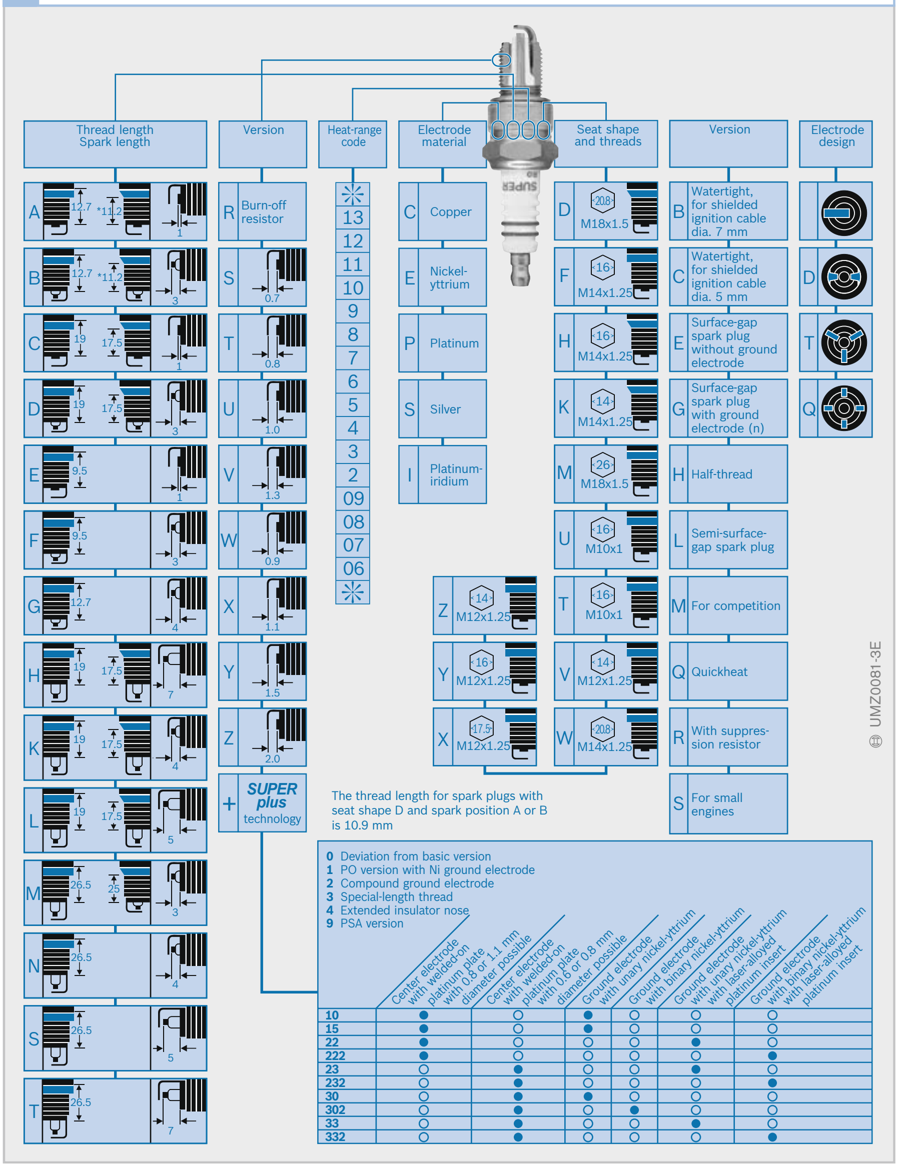


Fig. 13
1 Special conductive glass seal (interference-suppression resistor)
2 Ignition-cable connection
3 Shielding sleeve

Spark-plug type designations

Spark-plugs types are identified by a type designation (Fig. 1). This type designation contains all the spark-plug's data – with the exception of the electrode gap. The electrode gap is specified on the packaging. The spark plug which is suitable for a given engine is specified or recommended by the engine manufacturer and by Bosch.

1 Key to type designations for Bosch spark plugs



	Center electrode with welded-on platinum plate with 0.8 or 1.1 mm diameter possible	Center electrode with welded-on platinum plate with 0.6 or 0.8 mm diameter possible	Ground electrode with unary nickel-yttrium	Ground electrode with binary nickel-yttrium	Ground electrode with unary nickel-yttrium with laser-alloyed platinum insert	Ground electrode with binary nickel-yttrium with laser-alloyed platinum insert
10	●	○	●	○	○	○
15	●	○	●	○	○	○
22	●	○	○	○	●	○
222	●	○	○	○	○	●
23	○	●	○	○	●	○
232	○	●	○	○	○	●
30	○	●	●	○	○	○
302	○	●	○	●	○	○
33	○	●	○	○	●	○
332	○	●	○	○	○	●

Manufacture of spark plugs

Each day roughly one million spark plugs emerge from our Bamberg plant, the only Bosch facility manufacturing these products within Europe. Spark plugs conforming to the universal Bosch quality standards are also produced for local markets and original-equimpent customers in plants in India, Brazil, China, and Russia. Bosch has now produced a total of more than seven billion spark plugs.

The individual components joined to form the finished spark plug in final assembly are created in three parallel manufacturing processes.

Insulator

The basic material used in the high-quality ceramic insulator is aluminum oxide. Aggregate materials and binders are added to this aluminum oxide, which is then ground to a fine consistency. The granulate is poured into molds and processed at high pressure. This gives the raw castings their internal shape. The outer contours are ground to produce the soft core, which already displays a strong similarity to the later plug core. The next work step involves mechanically anchoring a platinum pin only a few millimeters in length in the soft core. The ceramic elements pass through a sintering furnace, where they obtain their final shape at a temperature of approximately 1600 °C, and the platinum pins are secured in the ceramic element. The soft core must be manufactured to compensate for the contraction that occurs in the sintering process, which is approximately 20 %.

Once the insulators have been fired, the labeling is applied to the insulator nose, which is then coated with a lead-free glaze.

Plug core

Electrical contacting with the platinum pin is effected by means of a contact pin, which is flattened at the rear end. This blade ensures subsequent secure anchoring in the plug core. *Paste* is filled into the hole once the center electrode has been inserted into the insulator. The paste consists of glass particles, to which conductive particles are added to produce a conductive connection to the terminal stud after sealing in. The individual components can also be varied to manipulate the paste's resistance. Resistance values of up to 10 kΩ can be achieved.

The *terminal stud* is manufactured from wire and formed by flattening and edge knurling. It receives a protective nickel surface and is inserted in the plug core. The plug core then passes through an oven, where it is heated to over 850 °C. The paste becomes molten at these temperatures. It flows around the center electrode and the terminal stud can then be pressed into this molten mass. The core cools to form a gas-tight and electrically conductive connection between the center electrode and the terminal stud.

Shell

The shell is manufactured from steel by means of extrusion. A section several centimeters in length is cut from the wire and then cold-formed in several pressing operations until the spark-plug shell assumes its final contours. Only a limited number of machining operations (to produce shrinkage and threaded sections) is then required. After the ground electrodes (up to four, depending on spark-plug type) have been welded to the shell, the thread is rolled and the entire shell is nickel-plated for protection against corrosion.

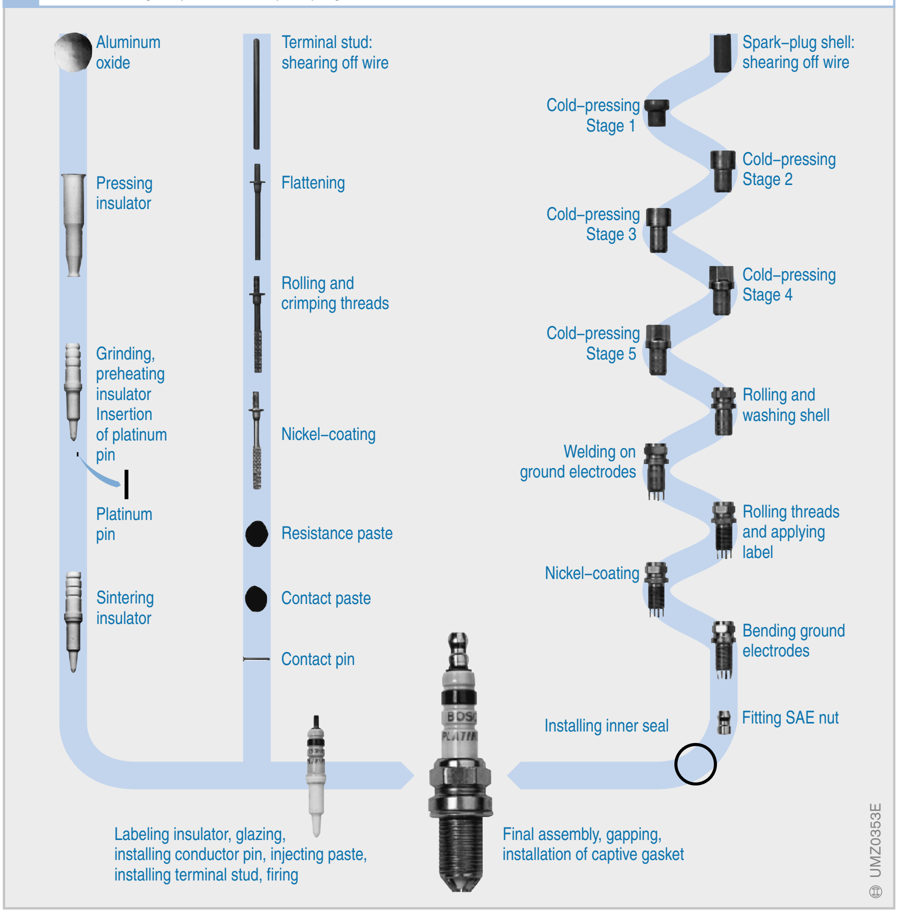
Spark-plug assembly

During spark-plug assembly, a sealing ring and the plug core are installed in the spark-plug shell. The upper shell is crimped and beaded to position the plug core. A subsequent shrinking process (induction is used to heat parts of the spark-plug shell to over 900 °C) provides a gas-tight union between spark-plug shell and core. Then an outer sealing ring is mounted on flat-seat spark plugs in an operation that reshapes the material to form a captive seal washer. This ensures that the combustion chamber will be effectively sealed when the spark plug is subsequently installed in a cylinder head.

On some spark-plug versions, an SAE nut must then be installed on the terminal stud's M4 thread and staked several times to form a firm attachment.

The assembly process is completed once the electrode gap has been adjusted to the engine manufacturer's specifications. The spark plugs are then prepared for sale in market- and customer-specific packaging.

1 Manufacturing sequence for a spark plug



Simulation-based spark-plug development

The Finite Element Method (FEM) is a mathematical approximation procedure for solving differential equations which describe the behavior and properties of physical systems. The process entails dividing structures into individual sectors, or finite elements.

In spark-plug design, FEM is employed to calculate temperature fields, electrical fields, and problems of structural mechanics. It makes it possible to determine the effects of changes to a spark plug's geometry and constituent materials, and variations in general environmental conditions, in advance, without extensive testing. The results provide the basis for precisely focused production of test samples which are then used for verification of the calculation results.

Temperature field

The maximum temperatures of the ceramic insulator and the center electrode in the combustion chamber are decisive factors for the spark plug's heat range. Figure 1a shows an axisymmetrical model of a spark plug along with a section of the cylinder head. The temperature fields as indicated in the colored sections show that the highest temperatures occur at the nose of the ceramic insulator.

Electrical field

The high voltage applied at the moment of ignition is intended to generate flashover at the electrodes. Breakdown in the ceramic material or current tracking between the ceramic insulator and the spark-plug shell can lead to delayed combustion and ignition misses. Figure 1b shows an axisymmetrical model with the corresponding field-strength vectors between center electrode and shell. The electrical field penetrates the nonconductive ceramic material and the intermediate gas.

Structural mechanics

High pressures within the combustion chamber during combustion make a gastight union between the spark-plug shell and the insulator essential. Figure 1c shows an axisymmetrical model of a spark plug after the shell is crimped and heat-shrunk. The retention force and the mechanical stress in the spark-plug shell are measured.

1 FEM application on a spark plug

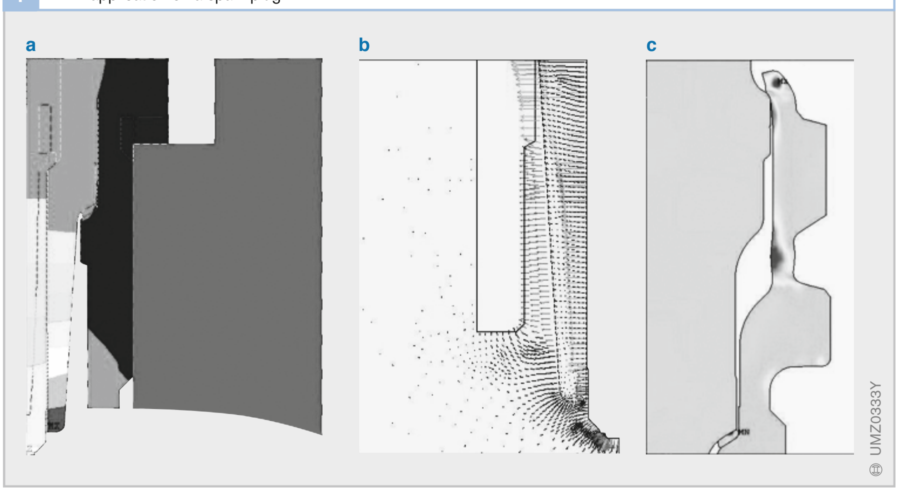


Fig. 1
Axisymmetrical models of a spark plug
- a Temperature distribution in ceramic insulator and in center electrode
- b Electric field strength adjacent to center electrode and shell
- c Retaining force and mechanical stress in spark-plug shell

Handling spark plugs

Spark-plug installation

Correct selection and installation will ensure that the spark plug continues to serve as a reliable component within the overall ignition system.

Readjusting the electrode gap is recommended only on spark plugs with front electrodes. Because this would involve actually changing the spark-plug concept, the gaps of the ground electrodes on surface-gap and surface-air-gap spark plugs should never be readjusted.

Removal

The first step is to screw out the spark plug by several thread turns. The spark-plug well is then cleaned using compressed air or a brush to prevent dirt particles from becoming lodged in the cylinder head threads or entering the combustion chamber. It is only after this operation that the spark plug should be completely unscrewed and removed.

To avoid damaging the threads in the cylinder head, respond to any tendency to seize in spark plugs by unscrewing them by only a small amount. Then apply oil or a solvent containing oil to the threads and screw the spark plug back in. Wait for the penetrating oil to work, then screw the plug back out all the way.

Installation

Please observe the following when installing the spark plug in the engine:

- The contact surfaces between spark plug and engine must be clean and free of all contamination.
- Bosch spark plugs are coated with anticorrosion oil, thus eliminating the need for any other lubricant. Because the threads are nickel-plated, they will not seize in response to heat.

Wherever possible, spark plugs should be tightened down with a torque wrench. The torque applied to the spark plug's 6-point fitting is transferred to the seat and the socket's threads. Application of excessive torque or failure to keep the socket attachment correctly aligned within the spark-plug well can place stress on the shell and loosen the insulator. This destroys the spark plug's thermal-response properties and can lead to engine damage. This is one reason why torque should never be applied beyond the specified level. The specified tightening torques apply to new spark plugs, with a light coating of oil.

Under actual field conditions, spark plugs are often installed without a torque wrench. As a result, too much torque is usually used to install spark plugs. Bosch recommends the following procedure:

First: Screw the spark plug into the clean socket by hand until it is too tight to continue. Then apply the spark-plug wrench. At this point, we distinguish between:

- New spark plugs with flat seal seats, which are tightened by an angle of approximately 90° after initial resistance to turning
- Used spark plugs with flat seal seats, which are tightened by an angle of approximately 30°
- Spark plugs with conical seal seats, which are tightened by an angle of approximately 15°

Second: Do not allow the socket wrench to tilt to an angle relative to the plug while either tightening or loosening; this would apply excessive vertical or lateral force to the insulator, making the plug unsuitable for use.

Third: When socket wrench with a loose mandrel, ensure that the opening for the mandrel is above the top of the spark plug to allow the mandrel to be drawn through the socket wrench. If the opening is too low on the plug, resulting in the mandrel only engaging a short distance, spark plug damage can result.

Mistakes and their consequences

Only spark plugs specified by the engine manufacturer or as recommended by Bosch should be installed. Drivers should consult the professionals at a Bosch service center to avoid the possibility of incorrect spark-plug selection. Sales assistance and guidance are available from catalogues, sales displays with reference charts and application guides available on the premises.

Use of the wrong spark-plug type can lead to serious engine damage. The most frequently encountered mistakes are:

- Incorrect heat-range code number
- Incorrect thread length, or
- Modifications to the seal seat

Incorrect heat-range code number

It is essential to ensure that the spark plug's heat range corresponds to the engine manufacturer's specifications and/or Bosch recommendations. Use of spark plugs with a heat-range code number other than that specified for the specific engine can cause auto-ignition.

Incorrect thread length

The length of the threads on the spark plug must correspond precisely to the depth of the socket in the cylinder head. If the threads are too long, the spark plug will protrude too far into the combustion chamber.
Possible consequences:

- Piston damage
- Carbon residue baked onto the spark-plug threads can make it impossible to remove the plug, or
- Overheated spark plugs

A threaded section that is too short will prevent the spark plug from reaching far enough into the combustion chamber.
Possible consequences:

- Poor ignition and flame propagation to the mixture
- The spark plug fails to reach its burn-off (self-cleaning) temperature, and
- The lower threads in the cylinder head's socket become coated with baked-on carbon residue

Modifications to the seal seat

Never install a sealing ring, shim or washer on a spark plug featuring a conical, or tapered, seal seat. On spark plugs with a flat seal seat, use only the captive sealing ring already installed on the plug. Never remove this sealing ring, and do not replace it with another shim or washer of any kind.

The sealing ring prevents the spark plug from protruding too far into the combustion chamber. This reduces the efficiency of thermal transfer from the spark-plug shell to the cylinder head, while also preventing an effective seal at the mating surfaces.

Installation of a supplementary sealing ring prevents the spark plug from penetrating far enough into its socket, which also reduces thermal transfer between the spark plug-shell and the cylinder head.

Spark-plug profiles

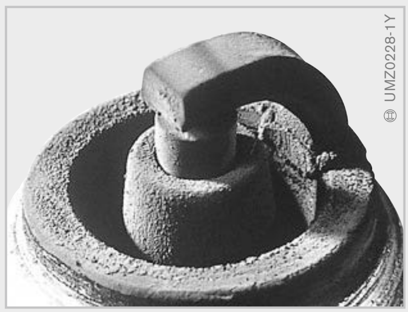
Spark-plug profiles provide information on the performance of both engine and plugs. The appearance of the spark plug's electrodes and insulator – the spark-plug profile – provides indications as to how the spark plug is performing, as well as to the composition of the induction mixture and the combustion process within the engine (Figs. 1 to 3, following pages).

Assessing the spark-plug profiles is thus an important part of the engine-diagnosis procedure. It is essential to observe the following procedure in order to obtain accurate results: The vehicle must be driven before the spark-plug profiles can be assessed. If the engine is run for an extended period at idle, and especially after cold starts, carbon residue will form, preventing an accurate assessment of the spark plug's condition. The vehicle should first be driven a distance of 10 kilometers (6 miles) at various engine speeds and under moderate load. Avoid extended idling before switching off the engine.

1 Spark-plug profiles, Part 1

① **Normal.**
Insulator tip with color between grayish white-grayish yellow to russet. Engine satisfactory. Correct heat range. Mixture adjustment and ignition timing are good, no ignition miss, cold-starting device functioning properly. No residue from leaded fuel additives or engine-oil alloying constituents. No overheating.

② **Sooted.**
Insulator tip, electrodes and spark-plug shell covered with a felt-textured, matt-black coating of soot.
Cause: Incorrect mixture adjustment (carburetor, injection): mixture too rich, extremely dirty air filter, automatic choke or choke cable defective, vehicle used only for extremely short hauls, spark plug too cold, heat-range code number too low.
Effects: Ignition miss, poor cold starts.
Corrective action: Adjust mixture and starting device, check air filter.



③ **Oil-fouled.**
Insulator tip, electrodes and spark-plug shell covered with shiny, oily layer of soot or carbon.
Cause: Excessive oil in combustion chamber. Oil level too high, severe wear on piston rings, cylinders and valve guides.
Two-stroke engines: too much oil in fuel mixture.
Effects: Ignition miss, poor starting.
Corrective action: Overhaul engine, use correct oil/fuel mixture, replace spark plugs.

④ **Lead fouling.**
A brownish-yellow glaze, possibly with a greenish tint, forms on the insulator tip.
Cause: Fuel additives containing lead. The glaze forms when the engine is operated under high loads after extended part-load operation.
Effects: At higher loads, the coating becomes electrically conductive, leading to ignition miss.
Corrective action: New spark plugs, cleaning is pointless.

2 Spark-plug profiles, Part 2

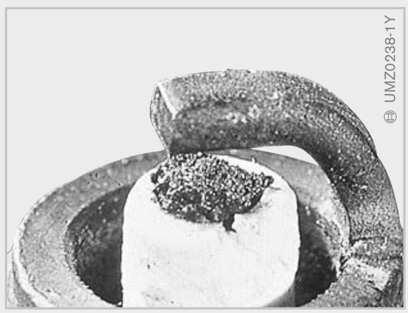
⑤ **Severe lead fouling.**
Thick, brownish-yellow glaze with possible green tint forms on the insulator tip.
Cause: Fuel additives containing lead: the glaze forms during operation under heavy loads following an extended period of part-load operation.
Effects: At higher loads, the coating becomes electrically conductive, leading to ignition miss.
Corrective action: New spark plugs. Cleaning is pointless.


UMZ0234-1Y

⑥ **Ash deposits.**
Serious ash residue from oil and fuel additives on the insulator tip, in the breathing space (annular gap) and on the ground electrode. Loose or cinder-flake deposits.
Cause: Substances from additives, especially those used for oil, can leave these ash deposits in the combustion chamber and on the spark plug.
Effect: Can produce auto-ignition with power loss as well as engine damage.
Corrective action: Restore engine to satisfactory operating condition. Replace spark plugs, change oil as indicated.


UMZ0236-1Y

⑦ **Melted center electrode.**
Melted center electrode, insulator tip is soft, porous and spongy.
Cause: Thermal overloading due to auto-ignition. Can stem from overadvanced ignition timing, residue in the combustion chamber, defective valves, faulty ignition distributor and low-quality fuel. May also possibly be caused by heat range that is too low.
Effects: Ignition miss, lost power (engine damage).
Corrective action: Check engine, ignition and mixture preparation. Install new spark plugs with correct heat range.


UMZ0238-1Y

⑧ **Center electrode with severe heat erosion.**
Severe heat erosion on center electrode, simultaneous serious damage to ground electrode.
Cause: Thermal overloading due to auto-ignition. Can stem from overadvanced ignition timing, residue in the combustion chamber, defective valves, faulty ignition distributor and low-quality fuel.
Effects: Ignition miss, power loss, possible engine damage. Insulator tip may rupture from overheated center electrode.
Corrective action: Check engine, ignition and mixture preparation. Replace spark plugs.


UMZ0239-1Y

3 Spark-plug profiles, Part 3

⑨ Melted electrodes.
Electrodes melted to form a cauliflower pattern. Possibly with deposits from other sources.
Cause: Thermal overloading due to auto-ignition. Can stem from overadvanced ignition timing, residue in the combustion chamber, defective valves, faulty ignition distributor and low-quality fuel.
Effect: Power loss followed by complete engine failure (engine damage).
Corrective action: Check engine, ignition and mixture preparation. Replace spark plugs.

⑩ Severely eroded center electrode.
Cause: Failure to observe spark-plug replacement intervals.
Effects: Ignition miss, especially during acceleration (ignition voltage not adequate for bridging wider electrode gap). Poor starting.
Corrective action: New spark plugs.

⑪ Severely eroded ground electrode.
Cause: Aggressive fuel and oil additives. Deposits or other factors interfering with flow patterns in combustion chamber. Engine knock. No thermal overloading.
Effects: Ignition miss, especially during acceleration (ignition voltage not adequate to bridge across electrode gap). Poor starting.
Corrective action: New spark plugs.

⑫ Insulator-tip breakage.
Cause: Mechanical damage (e.g., impact, fall or pressure on the center electrode from incorrect handling). In extreme cases, the insulator tip may be split by deposits between the center electrode and the insulator tip, or by corrosion in the center electrode (especially when replacement intervals are not observed).
Effect: Ignition miss. Flashover occurs in locations with no reliable access to the fresh mixture.
Corrective action: New spark plugs.