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Kinds and applications of various micro-welding processes: various direct welding in mini to micro welding

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1. Introduction

1.1 *Direct welding*

In the electrical welding for electronics and electrical packaging industries, soldering has been widely employed. However, it requires measures to avoid the use of lead in the process, and also various problematic issues in employing soldering have been pointed out. In addition, in assembling electronic products for electrical equipment for electrically-run automobiles, the improvement in weld quality is essential and hence it has become an urgent task to establish solder-free welding processes because stable weld performance has become necessary in their harsh service conditions such as heat, vibration and water.

This article's theme, direct welding, is the generic term for all the techniques for enabling the objects for joining to be welded without using intermediate materials such as solder, and it includes electron beam, laser, arc, ultrasonic, and resistance welding processes.

1.2 *What is micro-welding?*

Micro-welding is defined by the JIS Terminology as 'the generic term for welding processes which are applied to the sections to be welded which, owing to their extremely small sizes, are affected by the fusion quantity, diffusion thickness, deformation quantity, surface tension, and so on, all of which would not cause much problem when the joining sections are large, to produce an non-ignorable level of effect on weldability and weld quality and hence their effect on dimensions have to be given special attention'.

In the electronics and electrical packaging industries, micro-welding has been used extensively for electrical joining. These industries have been anxiously awaiting the development of electrically-stable welding processes which do not induce significant thermal effect and the occurrence of splashing (metal flash).

To obtain the required weld quality, welding machines which can set welding conditions rigorously have been employed. Those machines and devices are called micro-resistance welding and micro-TIG welding machines as the machines differ from usual TIG and resistance welding machines. These have been the main machines used to conduct direct welding in the mini- to micro-scale welding.

1.3 *History of direct welding in mini- to micro-scale welding*

Among direct welding methods where intermediate materials are not required, resistance welding has a history of more than one hundred years. It was first employed extensively in the 1910s mass production of Ford's model T. Based on this principle, the micro-resistance welding technique was born and grown in the two fields which required it; the welding of high-melting point metals in the inside of vacuum tubes, and the assembling of orthodontic instruments in the dental medical surgery.

Direct welding methods were developed in the electrical joining of components used at high temperature, such as vacuum tubes, because low-melting-point intermediate materials such as solder could not be used. In addition, the welding of different materials which are non-ferrous metals such as tungsten, molybdenum and nickel was required. For these reasons, a new resistance heat emission type welding technique was born and superseded conventional resistance welding. An affiliated company of our company, MEC (former Peco Co., founded in 1908), was established in Germany and expanded in Europe. The techniques nurtured in vacuum tube assembly are now employed extensively in the assembly of electron tubes and high intensity lamps.

On the other hand, the materials applicable to orthodontic instruments were limited to a small selection of metals owing to their internal use in the body. Naturally, the use of solder containing lead was impossible, and hence they also required direct welding. Thus, a micro-resistance welding technique was employed as the dissimilar metal welding technique for non-ferrous metals. In this technique, too, an affiliated company of our company, MUC (former Unitek Co., founded in 1948) started with a resistance welding power device for supplying electricity for an extremely short time, and has now grown to become a world-class company in the micro-resistance welding field. At present, the company

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is manufacturing and selling machinery and devices for resistance and laser welding as direct welding appliances in the field of medical instruments and equipment.

To make sure that electrical joining at one or several points is carried out reliably, various industries have been talking of the necessity for monitoring the results of joining. At the initial stage of this demand, our company, Miyauchi Technos Co., started selling the Weld Checker (current monitoring instrument) for controlling the quality of resistance welding, all over the world. Now we are selling appliances for not only micro-resistance welding but also laser welding which is regarded as a future major direct welding process in micro-welding joining.

Incidentally, for the assembly of the interconnection bar which requires high current, we have also started selling appliances for micro-TIG welding which has high cost performance, as the direct fusion welding for copper.

Precision direct welding appliances sold by us are for micro-resistance, laser (YAG, fibre, semi-conductor) and micro-TIG welding, all of which are welding appliances designed to deal with the above-mentioned definition of micro-welding.

2. Micro-resistance welding

2.1 *Outline*

Micro-resistance welding is the technique in which the current is supplied to the metals to be welded while applying a certain level of pressure so that resistance heat and pressure force would induce them to be welded. Accordingly, intermediate materials such as solder and welding rod (consumables) are not required. Moreover, because welding is done with just several volts, it does not pose any risk for technicians and also it keeps the operational environment very clean because it hardly induces the occurrence of heat, smoke, spatter, light, etc. This micro-resistance welding has been recognised as the effective process to be applied to energy-saving and/or automated appliances owing to the stability of quality, superiority in cost performance and simplicity in operation and maintenance.

2.2 *Its difference from general resistance welding and characteristics*

Its difference from general resistance welding is that controlling with low pressure and for an extremely short time makes it possible to make full use of contact resistance (concentrated heat) and hence to weld the materials with different heat calorific capacities and/or fusion points.

Photo 1 shows the cross sectional photo of the micro-resistance welded section between a 0.15 mm thick nickel sheet and a 0.35 mm thick nickel-plated iron sheet. It shows the characteristic of a thin flat nugget formed with the interface of the welded section as the centre. Photo 2 shows the cross sectional photo of a usual resistance welded section using the same materials. Since fusion starts from the central section of the objects, as the principle of resistance welding dictates, the welded section at the interface has a thick fusion zone. This leads to heat strain and/or the occurrence of blow-holes as shown in Photo 2, and hence to problems in weld quality.

The largest difference between resistance welding and other welding techniques is that welding is realised by heat generated from the inside. Micro-resistance welding is the technique developed for the maximum exploitation of this principle. It is the technique in which consideration is given to how to heat only the interface to be joined efficiently. Therefore, it can be said that the technique is suitable for the joining of metals with different heat calorific capacity and of metals of different kinds.

Incidentally, this concept is the base of selecting welding conditions such as the current, welding time, pressure, electrode and electrode holder. Also, what is more important than the welding conditions is the design appropriate for the resistance welding of each object to be welded.

2.3 *About the weld interface*

Even when appliances for micro-resistance welding are used, according to the material of the object to be welded and the combination of materials, the state of the weld interface becomes different, i.e. fused or diffused or

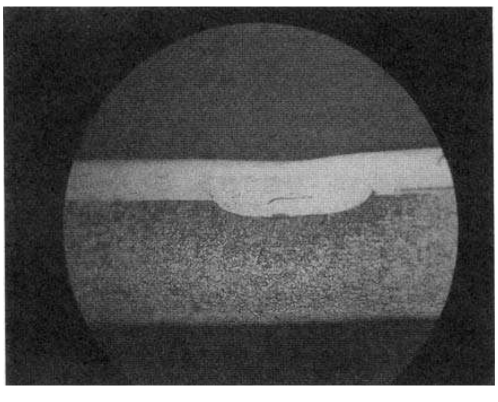

Photo 1. Cross sectional photo of micro-resistance weld (Nickel (0.15 mm) × nickel-plated iron (0.35 mm thick)).

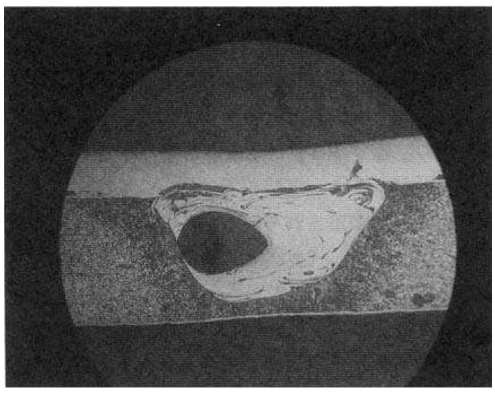

Photo 2. Cross sectional photo of usual resistance weld (Nickel (0.15 mm) × nickel-plated iron (0.35 mm thick)).

Photo 3. Micro-resistance welding monitoring device (Checker) [MM-370A].

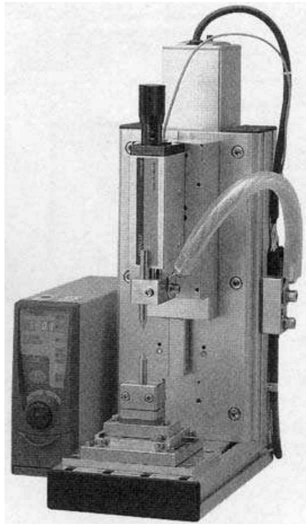

Photo 4. Motor driven welding pressure mechanism [MH-110A].

brazed. Even if the object to be welded, the electrode and the use of resistance heat at the contact point are the same, the state of the interface varies depending upon whether the temperature of the weld interface is raised to the melting point, or whether it is held at the diffusion temperature, or whether it is set at the temperature at which brazing filler metal responds.

With iron and ferrous alloys, the peculiar resistance heat and the contact resistance heat of the object to be welded are mainly used, and the welding mode is that of fusion welding in which nugget is produced.

With the welding of copper to copper, when fusion occurs at the interface, because of its good thermal conductivity, the welding electrode is also welded (deposited) and makes it impossible to continue the execution. Therefore, copper has been said to be unsuitable for resistance welding. However, it is possible to execute welding through diffusion at the weld interface by applying heat and pressure at below the melting point. In this case, resistance heat can be utilised to contribute to diffusion welding when tungsten or molybdenum is used for the electrode. Incidentally, it is also possible to use effectively, as the heat source, the current concentration by contact resistance and projection at low pressure. Executing diffusion welding in the liquid phase by using low melting point plate enables the weld strength and the stability of quality to improve. In this case, the weld interface does not have any residue of the metal with a low melting point.

The method to use an intermediate material which is different from those mentioned in this paper is the third type of welding, i.e. resistance brazing. It is employed for the high melting point brazing including that for titanium welding. This also makes it possible to induce internal heat to emit from the interface, hence to weld with low heat calories and within a short time, and as a result to execute welding in which thermal effect to the object to be welded is small.

2.4 *Fusing*

In the industry manufacturing coil products such as motors in which coated wires are used, the main welding technique had been the one of using solder. While studies were carried out to develop different solder from lead solder, direct welding without the use of solder was desired.

Fusing is the technique of using micro-resistance welding appliances which simultaneously conduct the peeling-off of the coating by using resistance heat, and the welding through diffusion. The coating material is softened by the heat emitted at the terminal, etc. and pushed out with the pressure force. This creates a conductive route between the copper wire and the terminal. Supplying high current into this route induces heat emission to enable diffusion welding.

2.5 *Welding process and its management*

The process of micro-resistance welding is usually

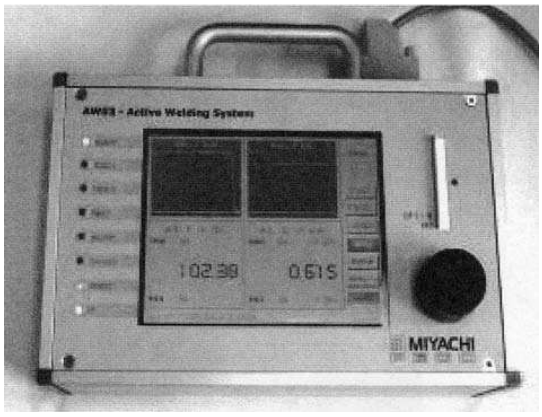

Photo 5. Process control unit (enables all together the setting and judging of checking conditions, the setting of pressurising process and the setting of the conditions for welding power).

divided into three stages, the initial pressurising time, the power supplying time and the pressure maintaining time. In the initial pressurising time, the vital point is how to obtain the current of a constant density stably, and this is the different point from that in usual resistance welding. The power supplying time is the stage from when the temperature is raised suddenly until fusion occurs (welding heat is emitted), and the stage when the object to be welded undergoes rapid displacement. After the power supply is finished, heat transfers itself to the electrode and the object to be welded, which then shows more gradual displacement during cooling solidification and this leads to welding.

To manage this process, micro-welding appliances are equipped with the function of detecting and checking of the initial workpiece height as the monitoring device for confirming the conditions, the function of checking, before the power supply, to confirm the pressure force and current density for monitoring the interrelations with current density, and the function of checking the power supply for monitoring the current, voltage and time set. Incidentally, the device to check displacement from the stage for power supply to the stage for cooling solidification was employed at first not as the above-mentioned condition monitor but as the quality monitor. Photo 3 shows the composite micro-resistance welding monitoring device mounted with various checking functions. Photo 4 shows the motor-driven welding pressure mechanism, the application of which has recently started owing to the importance of the initial pressure. Incidentally, in Germany, the introduction of a welding appliance has started which enables all together the setting and judging of the above-mentioned checking conditions, the setting of the pressurising process and the setting of the conditions for welding power. Photo 5 shows the process control unit.

3. Laser welding

3.1 *Outline*

Laser welding is used extensively from the assembly of electron guns and hard disk gimbals to the assembly of fibre optical light connectors and the manufacturing of precision sheet-metal processed products for portable appliances. As the components are becoming smaller, the introduction of laser welding is very effective because this process does not have a high degree of thermal effect or deformation. In addition, compared with resistance welding, it is superior in being able to operate the automatic device continuously since it does not require components such as resistance welding electrodes which need to be replaced in a short time. Moreover, the execution speed is very high, and hence, by using a scanner head, it is possible to perform spot-welding at over 50 spots per one second. Together with its characteristic of continuous operation, it will be a very important technique among the direct welding techniques for micro-welding fields.

The criteria for selecting a laser device used in welding are naturally a capability to supply the power density

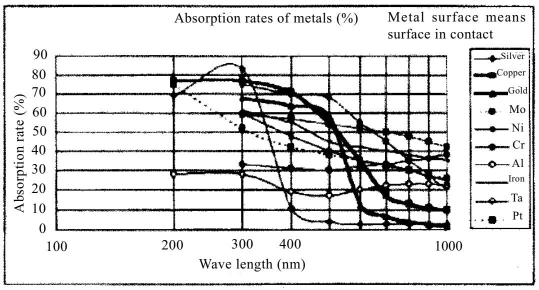

Figure 1. Absorption rates of metals.

high enough to induce fusion, but, with micro-welding in particular, the stability in output and the capability in creating the beam focal diameter in a short time so that thermal strain can be avoided. At the same time, with the welding of metals, the reflection rate of each metal has to be examined. This can be dealt with by selecting a laser wavelength with high absorption rate. Please see the reflection rates of metals in Figure 1.

Incidentally, the above description was given for the direct welding of a metal to a metal, but the processes for the direct welding of a resin to a resin, a resin to a metal and a resin to ceramics without using adhesive have recently been researched and developed, and the in-service application of some processes has started. They can be described as effective direct welding processes making use of (absorption penetration caused by the difference in the wave length of laser beams.

3.2 *Pulse Nd:YAG Laser (fundamental waves) device*

Laser used in this device is near infrared laser with 1.064 nm oscillated wave length. For micro-welding, short-time-welding is usually executed with the beam focal diameter of 100 μm to 400 μm and the output energy of several J to 100 J. When seam welding or scanner welding is conducted, the rated output is increased according to the speed.

This device is expected to be introduced even further in future owing to the in-service result of its extensive application to the direct welding for iron and nickel group materials with low reflection rate, and also because of the cost-wise advantage brought about in increasing the speed in spot welding and seam welding by combining it with the scanner head. However, for copper group materials, it has not been employed much on account of a problem in its low absorption rate.

3.3 *Secondary Harmonic Wave Pulse Nd:YAG Laser device*

This is a device with green laser beam in the visible light region in which the wavelength of YAG fundamental wave laser is halved (532 nm) so that the above-mentioned problem in absorption rate can be improved. With copper and gold, the absorption rate is 4.5 to 20 times higher than that of the basic wave laser. The in-service application of this device has just started as the one for the direct

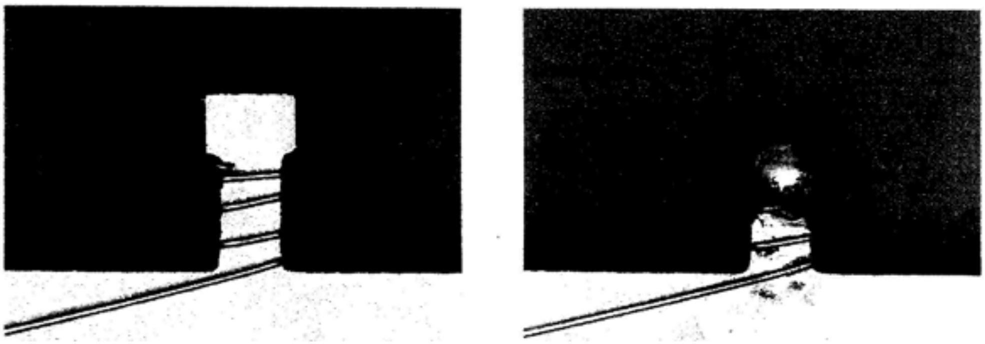

Photo 6. Example of TIG welded joint (Material: ϕ 0.15 coil (SF-FLW)/0.5 mm thick copper terminal).

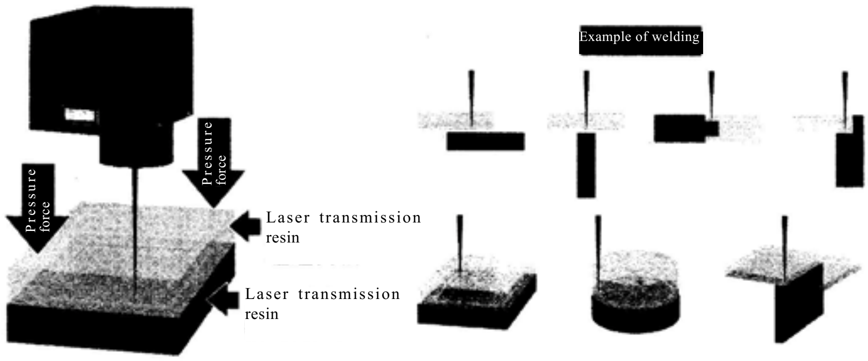

Figure 2. How resin welding works.

welding of copper wires onto the gold-plated printed circuit board as shown in Photo 6. It has a disadvantage in being incapable of obtaining high output, but studies are being continued to increase the output by the making of a hybrid with the fundamental wave laser.

3.4 *Semi-conductor laser device*

This is a device to apply semi-conductor laser beam directly to thermal processing without using crystal substance. Although it has an advantage in low price, it has been impossible to apply to direct welding of metals because it is not possible to improve heat generation efficiency by reducing the beam focal diameter as well as to produce the peak output with pulses. However, its application has started to the direct welding and soldering of resins which can be melted with low output. Particularly with the welding of resins, since heat can be emitted from the interface as in resistance welding, it is characterised as obtaining weld quality with only a low level of thermal effect.

With semi-conductor laser, it has become possible to combine it with optical devices so that it can obtain welded sections continuously, and hence it can be applied more extensively. Figure 2 shows a diagram to show its principle and an example of its application with the scanner head.

3.5 *Fibre laser device*

Fibre laser is a fibre oscillating method which was already proposed and developed in the 1960s. Because the excitation source was a lamp at that time, the characteristics of fibre laser were not made use of. However, in recent years, with the improvement in the output of the semi-conductor laser, it is drawing attention as the processing laser for the next generation because the quality of laser beam and the oscillation efficiency are much higher than those of the conventional laser.

Particularly important is the capability of obtaining an extremely high power density since it enables focusing on a minute spot of approximately several tens of μm. It is effective for the micro-welding of minute joints and the welding of metals such as copper with low absorption rate. Moreover, since it does not have thermal lens effect unlike YAG laser, even when it is used continuously, stable energy can be obtained. In this respect, too, it has the conditions required for micro-welding. Owing to its ability in producing a beam reduced to a minute spot, and its stability at a high speed, the expectation for it is very high as the direct welding process which would replace the re-flow welding.

3.6 *Quality control of laser*

With our company's laser welding machines, including fibre laser devices, control is basically done by power feedback control. Laser output within the excitation module is measured in real time, and the laser output sampled is compared with the waveform set to acquire the real time power feedback. According to the feedback, the energy put into the lamp is changed so that the

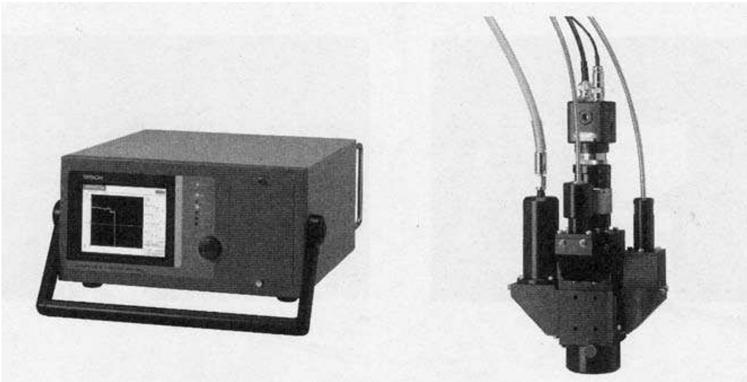

Photo 7. Laser welding monitor (main part) [MML-100A] and exit unit for MML-100A.

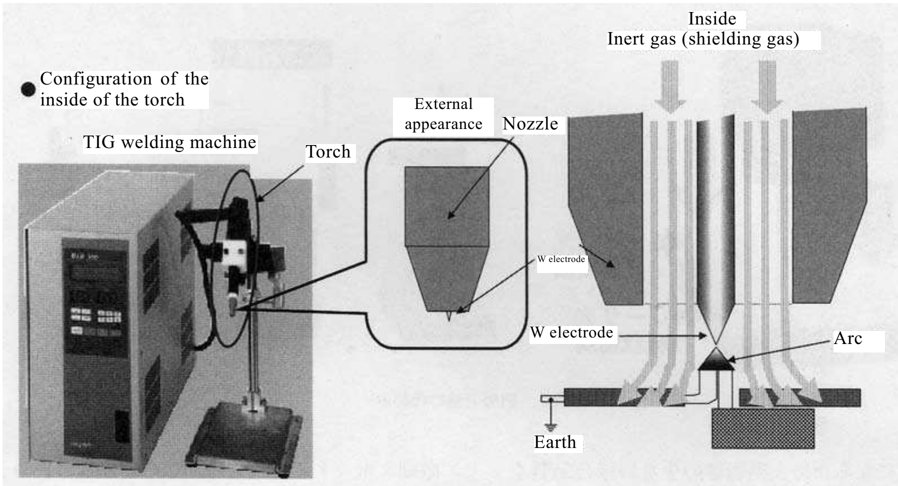

Figure 3. Principle of TIG welding.

waveform set will re-appear to obtain the ideal laser output waveform.

Incidentally, our company has now started to sell the laser welding monitor as shown in Photo 7. This device can be used only for the wave length of YAG, but it is proposing to control the quality of laser weld by monitoring the laser output at the fibre exit end and the change in the light reflected from the point being welded.

4 Micro-TIG welding

4.1 *Outline*

This is a technique developed by making use of the principle of usual TIG welding to apply to the field of micro-welding. Although TIG welding is also an effective direct method without using the intermediate materials, it was not investigated as a welding process for electric and electronic areas.

With the electrification of automobiles, the technique required for the welded sections used in the particularly fierce environment in automobiles was considered to be fusion welding or high temperature brazing and not diffusion welding methods of copper group metals such as micro-resistance welding and ultrasonic welding. At first, owing to the demand for not using any intermediate materials, laser and electron beam welding processes were investigated as direct welding, but they could not be employed on account of cost and workability.

In these contexts, the studies started to apply TIG welding with a long standing history of applications to the welding of non-ferrous metals, and the technique and its executing machinery have been established. Here, too, since the components to be welded are smaller and made of more difficult materials than conventional ones, the principle of micro-welding was applied and the micro-TIG welding technique was realised by employing a power source with capability of setting the output by 1 ms and 1 A as well as with functions of current feedback and monitoring.

4.2 *Principle*

The fundamental principle of this welding method is the same as that of TIG (Tungsten-Inert-Gas) welding. As shown in Figure 3, inert gas such as argon (Ar) is supplied from the inside of the welding torch into the nozzle to induce the arc to be generated in the inert gas atmosphere between the tungsten (W) electrode and the

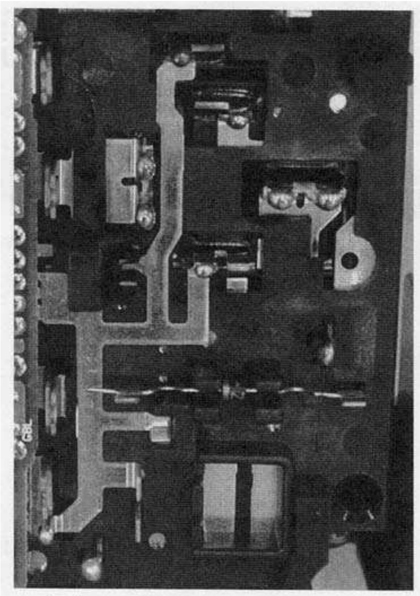

Photo 8. Electronic control module package.

object to be welded. The arc heat is used to melt the object to be welded so that the welding can occur.

In micro-TIG welding, which enables fine control, it is possible to deal with the fusion welding for mini-components.

4.3 *Applications*

The initial applications of this method were as the measure to avoid the use of solder to the welding of coated wires and terminals in coil components such as chip coils, miniature relays and small vibration motors (Photo 7). Since there is more clearance in work precision than in laser welding, much expectation was held as the low cost device for components of resin-moulded products for which precision matters. The tip of the terminal melts and forms the fusion weld in the form of wrapping the wire. Coating is removed with the heat generated at the time and enables electrical joining. However, for coated wires with high thermal resistance, it is judged that the use of this technique is not possible because deterioration of strength is caused by the coating material. Direct welding methods recommended for this case are the above-described micro-resistance welding (fusing).

On the other hand, in the welding of copper terminals in the electronically controlled module package for automobiles, this method has shown greater advantage than those of resistance, ultrasonic, laser and electron beam welding. Fusion welding is obtainable at far lower cost than that of laser welding. Precision in positioning is not required to the same level, either. In addition, as described above, more stable weld strength is obtainable than by diffusion welding methods such as resistance and ultrasonic welding. In the automobile manufacturing industry, this method is employed in the assembly of the electronic control module package and of wire connections in the motor.

4.4 *Observation of welding state*

In micro-TIG welding, in which welding lasts a longer time than in laser welding, the state of welding can be observed by the usual high-speed camera. Welding conditions could be selected very easily in the experimental welding executed after the designing of the joint section is done to a certain extent.

Furthermore, the weld strength can also be checked by observing the alloying state of the melted zone with an electron microscope. Under this assurance, it is assumed that whether there is a blow-hole or not can be checked in non-destructive tests with X-ray filming.

In spite of the necessity of various measuring devices, it is evaluated as a welding technique very easy to employ when the ease in selecting conditions and the possibility of applying non-destructive tests are taken into account.

5. Conclusions

In the field of micro-welding, the application of direct welding in which intermediate materials such as brazing filler, solder and electrode are not used is becoming more common to reduce the impact on the environment and to improve the reliability in welding.

To enhance the application of direct welding further, it is important as a pre-requisite that welding conditions are easily obtainable and that quality can be secured. Our company would like to continue our research and development towards these themes so that environmentally friendly technology will be used more extensively.