Journal of Materials Science and Engineering A 12 (10-12) (2022) 107-114
doi: 10.17265/2161-6213/2022.10-12.001

Challenge to Welding and Joining Technology for Applying Multi-material in Electric Vehicle Production

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Abstract: Advanced high strength steel, aluminum alloy and plastic materials are used in the right places for the purpose of reducing the weight of EV (electric vehicle) bodies and in-vehicle parts, and multi-material structures are advancing. Therefore, it is difficult to handle the welding and joining processes of automobile structures by the conventional arc welding and resistance spot welding, which have been applied to steel joining, and various joining processes are being applied depending on the material. Under above mentioned background, the authors have developed some unique joining processes for multi-materials that are used in the right place. This paper introduces the dissimilar metal joining between the galvanized steel and aluminum alloy by laser arc hybrid process, the metal/thermoplastic dissimilar material joining using laser process and the solid-state resistance spot joining process of advanced high strength steel for EV body structural parts. Moreover, the authors describe the high-speed plasma jet GTA (Gas Tungusten Arc) welding process of copper applied to electrical components such as motors.

Key words: Arc welding, laser arc hybrid, dissimilar joining, spot joining, electric vehicle.

1. Introduction

The electrification of transportation equipment is progressing toward the realization of a carbon-free society, and especially, it is said that the ratio of EV (electric vehicle) will exceed 30% in the world automobile production in 2030 [1]. In EVs, weight reduction is required for vehicle body structural members to improve electricity costs, and the application of lightweight materials such as non-ferrous metals and plastic to the right place, that is, multi-materialization is promoted [2-4]. Therefore, it is difficult to handle the joining process in automobile structures only by arc welding and resistance welding, which have been conventionally used for steel. The application of new joining processes such as joining dissimilar metal of steel and aluminum alloys and joining dissimilar materials of metal and plastic is expected to increase [5, 6]. In addition, as the power source of automobile is replaced by an electric motor instead of an engine, fuel tanks and exhaust system parts made of galvanized steel or stainless steel are no longer required and replaced by batteries, motors and other electrical components made of aluminum, plastic, or copper. For this reason, in the joining process of in-vehicle parts, the GMA (Gas Metal Arc) welding, which has been the mainstream process, is being replaced by TIG/plasma welding, laser welding and adhesive bonding [5-7]. Above mentioned background, in order to respond to the multi-materialization in automotive body structures and in-vehicle components, the authors have been developing a process for joining dissimilar materials or copper without major changes in jig systems or consumable materials. This report introduces those development examples.

2. The State of Art Applying to Multi-materials and Their Joining for EV Construction

Fig. 1 shows an example of multi-materialization for body in white [3]. In this example, three types of

Corresponding author: Tomoyuki Ueyama, Dr. Eng., research fields: welding and joining process.

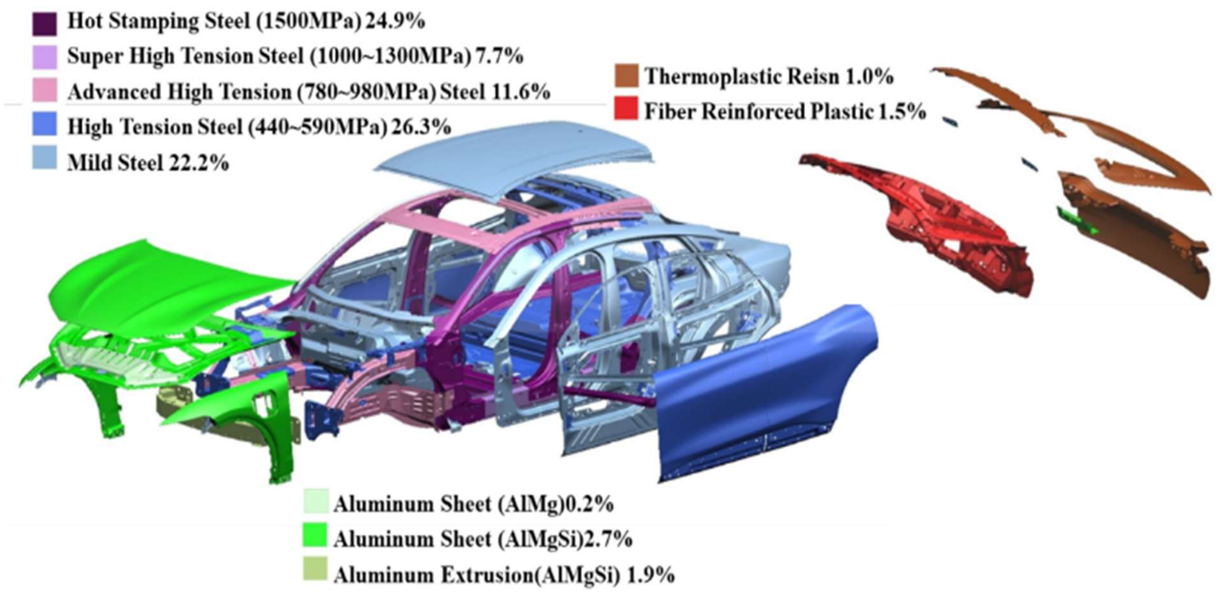

Fig. 1 Body in white and material constitution of EV.

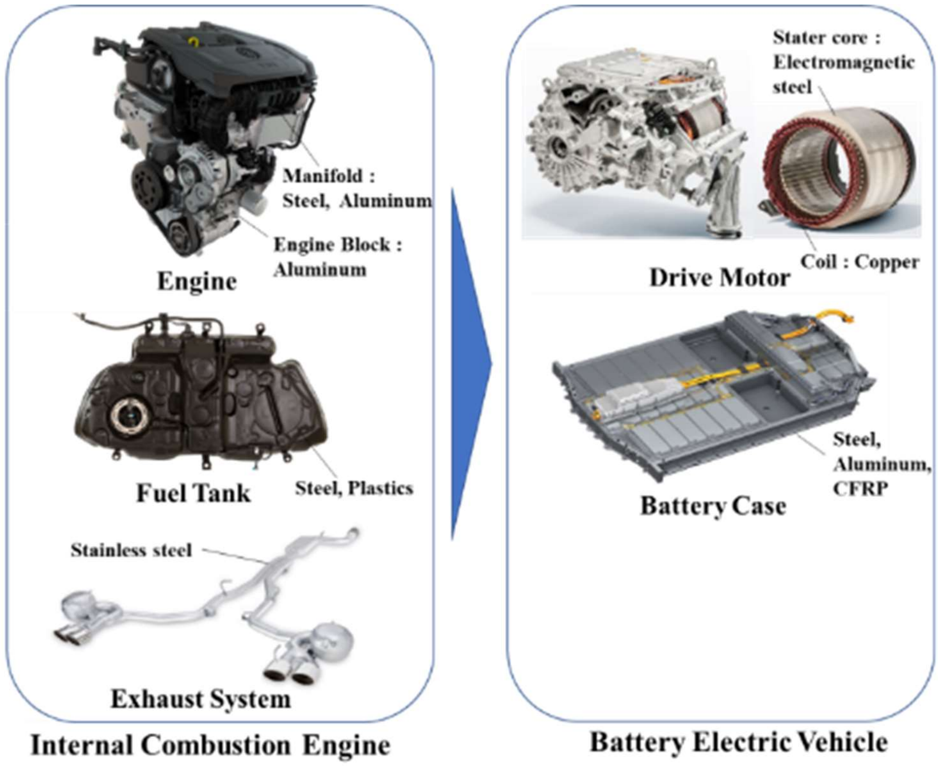

Fig. 2 Comparison of in-vehicle parts.

aluminum materials and five types of steel with different strength are applied in the right places on EV construction for reduction of body weight. In addition, thermoplastics and fiber reinforced plastics are also used as double structural members such as tailgates.

To combine these materials, various joining processes are applied, including joining not only between similar metals but also dissimilar metals such as steel and aluminum alloys. Furthermore, joining between different materials such as metal and plastic is also required. Thus, multi-material car body requires multi-joining processes [5].

Fig. 2 shows a comparison of major in-vehicle parts for engine vehicles and EVs. With the introduction of EVs, the component materials have changed from steel materials to aluminum, copper, and plastic, and the applicable joining method has also changed.

3. Recent Development Joining Process

3.1 Steel-Al Joining Using Laser Arc Hybrid Process

Many researches have been conducted on the joining process of dissimilar materials between hot-dip zinc coated steel (GI) and aluminum alloy [8-10], and it has reached a level where sufficient joining strength can be obtained. When joining alloyed zinc coated steel (GA) and an aluminum alloy, peeling occurs easily due to the formation of a brittle IMC (intermetallic compound) at the joining interface, and the convex bead formed due to the poor wettability of the bead toe (small contact angle).

The authors have developed a pulsed laser arc hybrid process that can suppress IMC generation and improve bead wettability while using commercially available aluminum alloy welding wires.

Fig. 3 shows the appearance of the developed system. By using a pulse output (6 kW) of laser irradiation, a wide bead shape with good wettability can be obtained by removing the alloyed zinc coated layer on the surface of steel sheet and improving the fluidity of the molten metal.

As shown in Fig. 4, there are overlap areas on the joined material by the laser irradiation area at one pulse and the next pulse. The overlap ratio is defined by the laser irradiation area S_N of one pulse and the overlap area S_A [11]. The heat input to the base metal can be controlled by adjusting the ON-OFF period of the laser output based on the overlap ratio, and the formation of IMC can also be controlled. The overlap ratio and the heat input to the base metal can be expressed as functions of the joining speed, pulse frequency, and pulse duty as shown in Eqs. (1) and (2), respectively.

$$OL\ ratio = \frac{S_A}{S_N} = \frac{W + \frac{v}{f}(D-1)}{W + \frac{v}{f}D} \tag{1}$$

$$Heat\ Input = \frac{P_{lh}D + IV}{v} \tag{2}$$

where, P_{lh}: Output power of pulsed laser (W), I: Arc current (A), V: Arc voltage (V), W: Width of square laser irradiation area in joining direction (mm), v: Joining speed (mm/s), f: Pulse frequency (Hz), D: Pulse duty (%).

Therefore, if the joining speed and the pulse duty are fixed and the optimum overlap ratio is determined, heat input to the base metal can be controlled by changing the pulse duty while the overlap ratio of the optimum value is fixed.

Fig. 5 shows the bead appearance of GA (Zn: 45 g/m^2) steel/A6063 lap joint obtained by setting the optimum overlap ratio (85%) and adjusting the pulse duty.

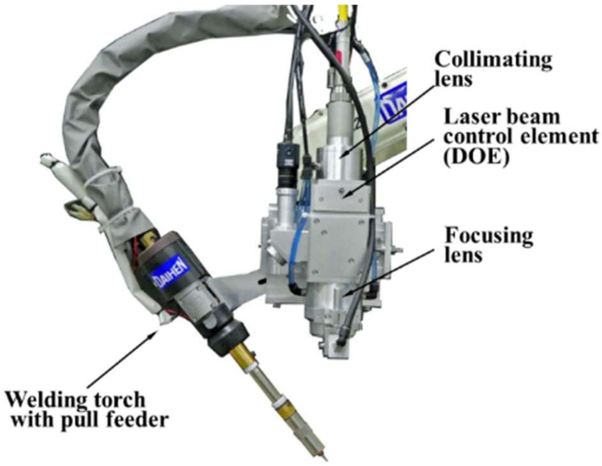

Fig. 3 Laser arc hybrid system.

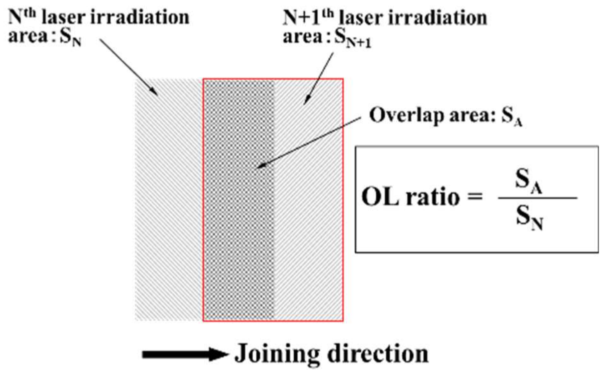

Fig. 4 Definition of OL (overlap) ratio.

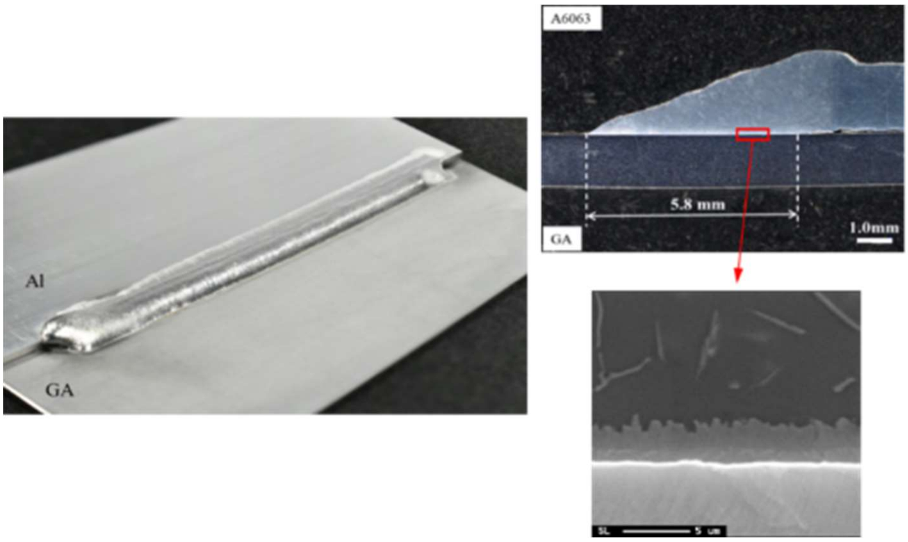

Fig. 5 Bead appearance and cross-section of GA/A6063 lap joint.

Good joining results were obtained without peeling of the joint portion, and the IMC layer thickness at the joint interface was about 4 to 6 μm.

3.2 Metal and Thermoplastic Dissimilar Material Joining Using Laser Process

Although adhesion and screw fastening are applied to joining dissimilar materials of metal/thermoplastic as the major processes in EV body structures, it is expected that demand for direct joining will increase from the viewpoint of shortening joining time and reducing running costs as mass production progresses. The authors have newly developed a metal/thermoplastic direct joining process that utilizes laser ablation and heating.

Fig. 6 shows the outline of this joining process. The metal surface forms micro-groove patterns by a laser ablation in a different direction, and the plastic is brought into close contact with the surface and irradiated with a laser from the metal side to heat and melt the plastic. The molten plastic is pressurized from the metal side to flow into the micro-groove patterns of the metal surface, and the anchor effect completes a strong joining.

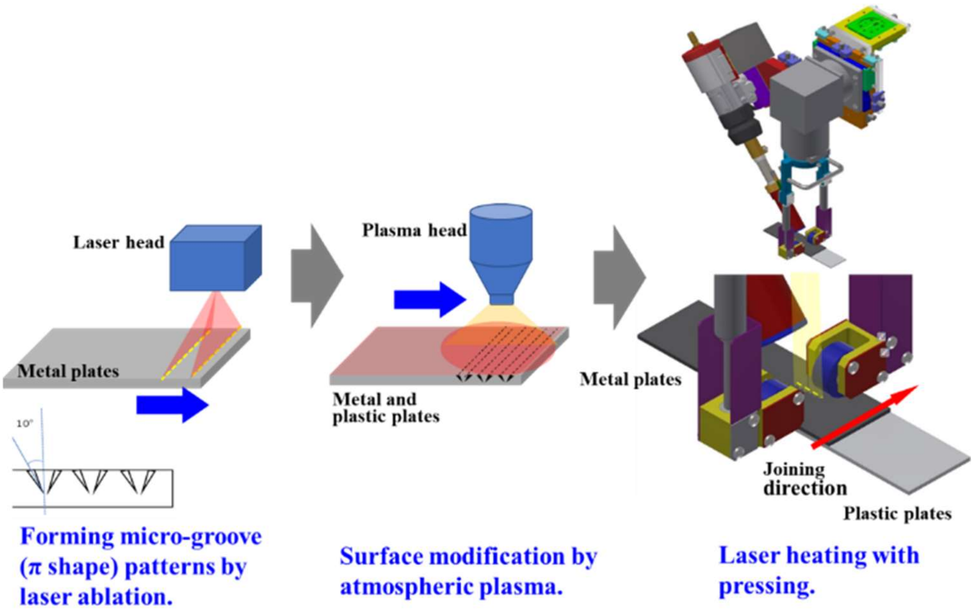

Fig. 6 Outline of metal/thermoplastic joining process.

Fig. 7 shows the tensile shear test results of the 980 MPa high strength steel and glass-fiber-reinforced thermoplastic joint. At a pressure of 20 N, plastics plate fracture occurred in the laser output range of 0.72 to 0.96 kW. When the applied pressure was increased to 40 N, the plastics plate fracture occurred under the wide range of conditions, and there was little variation of TSS (tensile shear strength) value. Fig. 8 shows the joint appearance after tensile shear test and cross-sectional macrostructure of the joint. The inflow of the plastic into the micro groove is observed, and it can be seen that the plastic is surely biting into the inside of the steel. It is considered that this exerted the anchor effect and contributed to the improvement of the strength showing the plastics fracture in the tensile shear test.

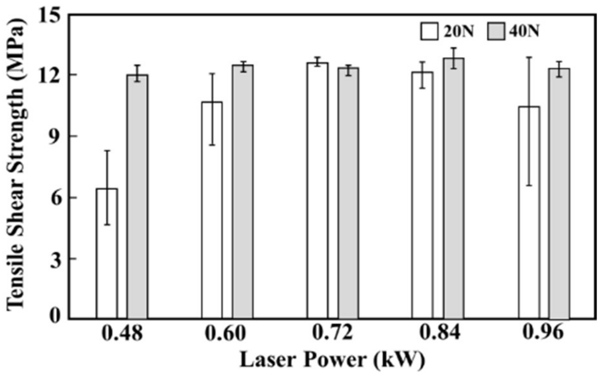

Fig. 7 TSS result of SPFC980/PP (SFT) joints.

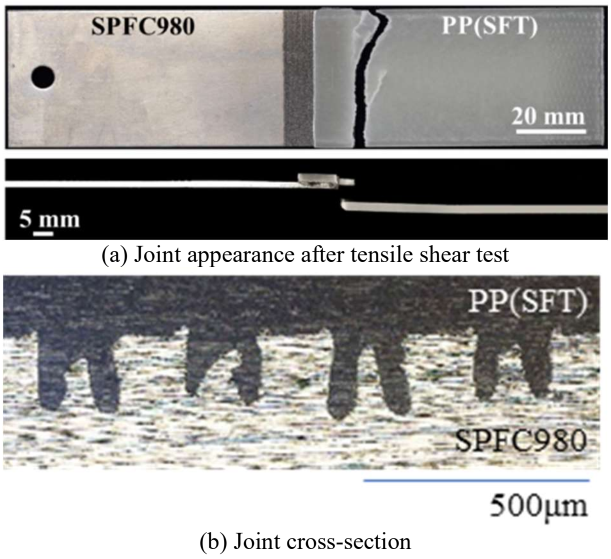

Fig. 8 Joint appearance and cross-section of SPFC980/PP (SFT) dissimilar material joining.

3.3 Solid State Resistance Spot Joining (Cold Spot Joining, CSJ) Process of Advanced High Strength Steel

Resistance spot welding is widely applied in the assembly of automobile bodies and automobile parts. In recent years, the proportion of advanced high strength steel and press hardness steel (hot stamping steel) applied to automobile parts has increased due to the need to reduce the weight of vehicle bodies. Compared to mild steel sheets, these high strength steel sheets do not fit well with each other when clamped by electrodes, have a narrow contact diameter, and do not easily expand the energizing area. Therefore, the resistance value becomes high and splash is likely to occur. In order to secure an appropriate nugget, high pressure, securing an appropriate energizing current, extending the energizing time, etc. are required, and the life of the copper electrode is shortened. A solid-state resistance spot joining (CSJ) that applies high pressure to the joining material to reduce the joining temperature and complete the joining at a lower temperature than the melting point, has been developed [12].

Fig. 9 shows the principle of CSJ process. First, the pressure is applied to the material to be joined and energized to raise the temperature at the interface of the material to be joined. As the temperature rises, the material near the interface begins to soften, and when the strength of the joining material falls below the applied pressure, deformation occurs and the impurity layer at the interface is discharged as burrs, and the new surfaces come into contact with each other to form a join.

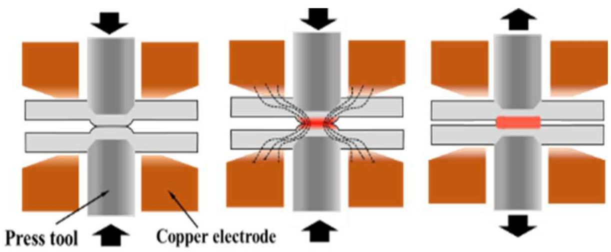

Fig. 9 Principle of CSJ process.

Fig. 10 shows the joint cross-section and hardness distribution of CSJ in carbon steel S45C (JIS G 4051) with a plate thickness of 1.6 mm and a C content of 0.45%. By applying a pressure of 450 MPa to the joining interface and energizing 3.5 kA, the base metal is softened, and unmelted joining is realized. The hardness of the entire joint is equivalent to that of the base metal, and no martensitic transformation has occurred. Fig. 11 shows the macro cross-section of a 980 MPa high strength steel sheets by CSJ. There is no unjoined portion on the entire joining interface, and a good joining portion is obtained.

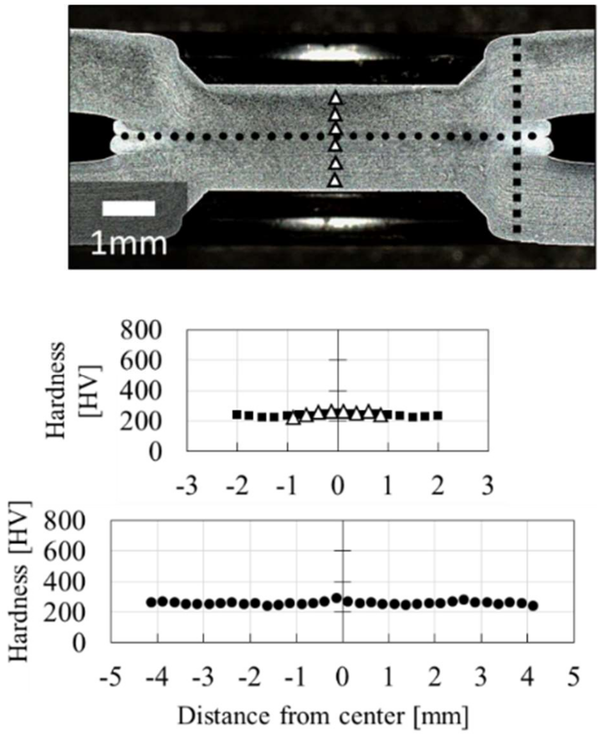

Fig. 10 Joint cross-section and hardness distribution.

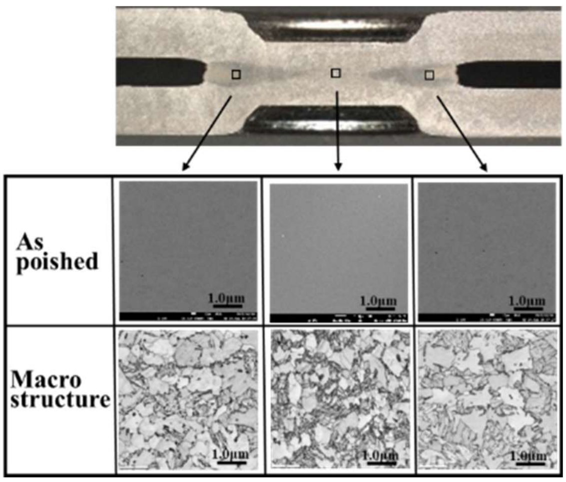

Fig. 11 Microstructure at joint interface of 980 MPa high strength steel.

3.4 Copper Joining Using Plasma Jet TIG (PJT) Process

EV drive motors are required to be compact, highly efficient, lightweight, and quiet, while they also play important roles in the system, such as main power at start-up, power assist during acceleration, and energy recovery during braking [13]. In addition to higher torque and output, drive motors are required to have higher power density due to lower-energy consumption, lower cost, and the need for downsizing caused space limitations. So, recent motors have distributed winding stator with segments conductor as shown in Fig. 12 [14].

It is also necessary to reduce the loss due to the winding resistance of the stator, which is one of the quality targets required for the joined parts of the rectangular copper wires that constitute the stator coil. Currently, the mainstream joining methods applied for them are TIG welding and laser welding. In particular, the advent of a blue laser with a wavelength of 350 nm has improved the laser absorption of copper, and high-efficiency welding has been proposed [15, 16].

The authors developed PJT process in which the arc is constricted by an inner gas flow with dual gas nozzles as shown in Fig. 13. The arc directionality and stability are secured by pulse current output of several hundred Hz, and welding can be completed in 150 ms per one

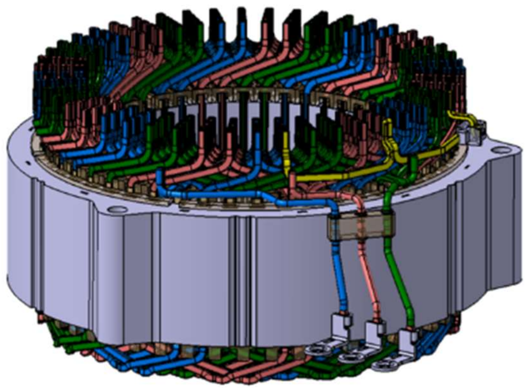

Fig. 12 Copper winding stator core.

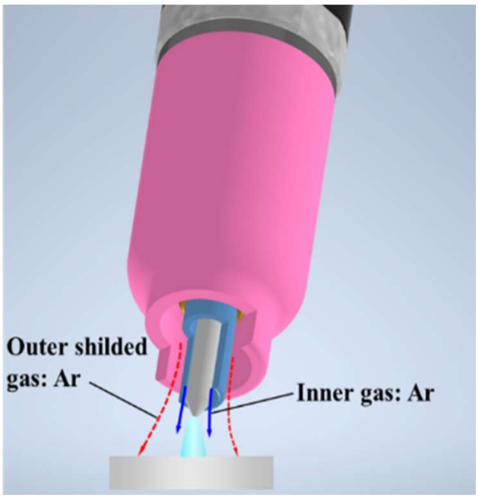

Fig. 13 Plasma jet TIG welding process.

joint. By using a welding system with multiple units of this welding method, we propose a process that is superior to laser welding in terms of efficiency, welding quality, and equipment cost.

Fig. 14 shows the melting phenomena of the rectangular copper wires by the constricted pulse arc and the current waveform control sequence. The PJT arc, which is more stiffness and directional than the conventional TIG arc, instantly melts and integrates the two rectangular magnet wire ends. And then, a downslope period of several 10 ms is provided to stop the arc, so that a hemispherical joint shape in which the ends of the rectangular magnet wires are always symmetrical can be obtained as shown in Fig. 15.

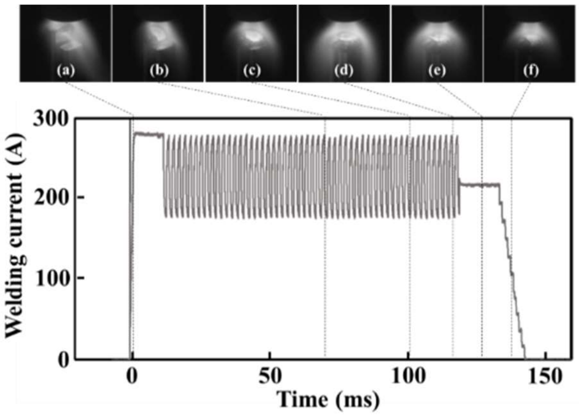

Fig. 14 One cycle of rectangular copper wire melting by PJT welding process.

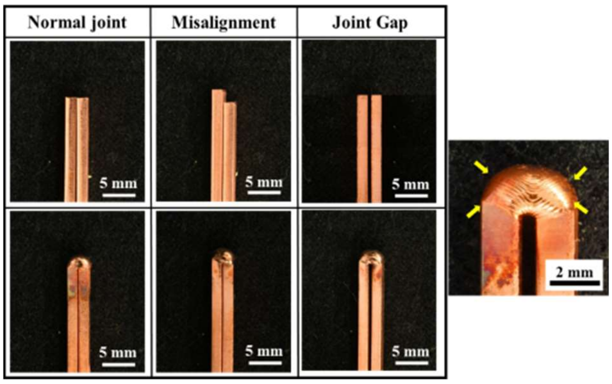

Fig. 15 Joining results of rectangular copper wire by PJT welding process.

4. Summary

This paper introduced the trend of developing the optimum joining process due to the multi-materialization of EV body and in-vehicle parts. The newly developed joining processes are summarized as follows.

(1) In the dissimilar metal joining of zinc coated steel/aluminum alloy plates by laser arc hybrid process, the required weld metal is filled by arc, and the zinc coated layer is removed and the wettability of the weld metal is improved by pulse laser. A good dissimilar material joint could be obtained.

(2) In metal/thermoplastic dissimilar material joining, the metal surface forms micro-groove patterns by a laser in a different direction, and the plastic is brought into close contact with the pre-treated metal surface and irradiated with a laser while pressurizing from the metal side to heat and melt the plastic. It was possible to obtain the joint strength leading to the breakage of the plastic base material.

(3) In CSJ process, non-transformation joining of high carbon steel is possible by applying high pressure while energization. In addition, good solid state joints of 980 MPa high strength steel sheets could be obtained.

(4) In copper welding by the plasma jet TIG process, short-time welding comparable to laser is possible in the welded joint of the stator coil of the electric motor, and a sound welded part could be obtained.

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