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Development of New Joining Technology for High-Perfomance Products

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Abstract:

Since entering new businesses in recent years Nippon Steel has developed welding, joining, and associated technologies for new materials and parts. They are: 1) wire bonding for integrated circuits (ICs), and laser beam welding of the metal protective tubes in optical fiber cables used in the electronics field; 2) transient liquid-phase (TLP) bonding and plasma spraying for repairing jet engine parts, and plasma spraying of functionally gradient materials (FGMs) in the aerospace field; 3) brazing of metal supports for catalytic converters, hardfacing of titanium alloy engine valves, and dissimilar-metal welding of steel and aluminum in the automobile field; 4) stud welding in the construction field; and 5) thermal spraying for ironmaking and steelmaking facilities.

1. Introduction

As Nippon Steel has launched many new businesses in recent years, the company has encountered increasing opportunities for supplying various functional materials and parts for use in such applications in the electronics, aerospace, automobiles, and construction fields. These opportunities have called for the development of new joining technology other than conventional welding technology for steel. We have tackled microjoining and precision joining by brazing, laser beams and ultrasonics, reviewed and improved conventional resistance spot welding and stud welding, and developed hardfacing and thermal spraying processes that are in close relation to conventional welding processes. Some of the new developments are introduced here. Although not related to the new businesses noted above, thermal spraying processes are also under development to achieve longer service life of ironmaking and steelmaking facilities. They are also discussed below.

2. Joining Technology for Electronics Parts

2.1 Wire bonding for integrated circuits

The progress of microelectronics has decreased the size and increased the functionality of electronic equipment. The packaging of integrated circuits (ICs), the building blocks of electronic equipment, has advanced toward smaller size as well. Wire bonding is one of the IC packaging technologies. As the wire pitch has decreased year by year, the reliability of wire bonds has assumed ever increasing importance. The basic wire bonding process is illustrated in **Fig. 1**. The end of the bonding wire is melted and formed into a ball by a discharge arc. The ball is bonded to the aluminum electrode by applying vertical pressure

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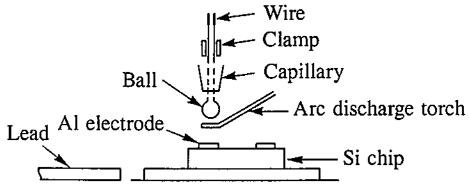


Fig. 1 Basic wire bonding process

Table 1 Wire bonding reliability items and influence factors

Reliability item	Influence factor
Bonding wire breakage	Wire and HAZ strength; HAZ (neck) fatigue
Wire/pad interface failure	Bond interface strength ·Strength immediately after bonding ·Strength after being heated at high temperature for long period of time
Short circuit by wire sweep	Wire strength and stiffness
Wire breakage by progress of corrosion	Corrosion of aluminum metallization

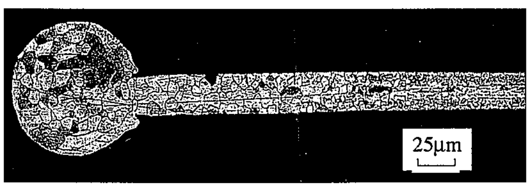


Photo 1 Microstructure near ball of bonding wire (25μm ϕ , 4N-Au)

with the capillary. As a joining mechanism, wire bonding can be described as a solid-state diffusion bonding process. Since a fine gold wire of about 25μm diameter is used, the resultant wire bond is 60 to 100μm in diameter. This means that wire bonding is the joining method that can produce the smallest possible joints now.

The problems of wire bonding in relation to the reliability of ICs are summarized in **Table 1**. The loss of strength in the heat-affected zone (HAZ) of the wire bond is an important issue for initial reliability (during fabrication or initial service). The bonding wire is made of 99.99% pure gold and is adjusted to the required strength by adding several ppm of dopant (alloying element) and heat treating it after drawing. When its end is formed into a ball for bonding, the wire is recrystallized and grain size increases when heated. The HAZ is generally low in strength[1]. The microstructure of a very fine gold wire examined by the polish/etch method is shown in **Photo 1**. Grain growth can be observed in the HAZ near the ball. A HAZ simulator capable of applying a thermal cycle equivalent to that encountered during ball formation was developed to measure the mechanical properties of the HAZ[1]. The construction of the simulator is shown in **Fig. 2**. A pulsed-current heating method with high heating capability is used. **Fig. 3** shows the HAZ fracture loads of various wires investigated using the simulator. The tensile strength ranges from 160 to 240MPa in the wire stage, decreases by 30 to 40% to a range of 100 to 160MPa in the HAZ, depending on the dopant composition[2]. These results led to the development of bonding wire with excellent HAZ properties.

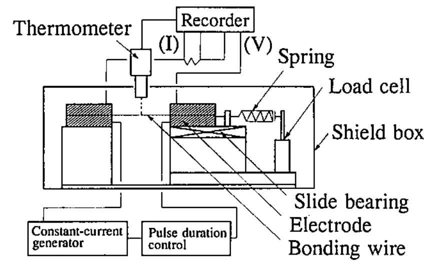


Fig. 2 Bonding wire HAZ simulator

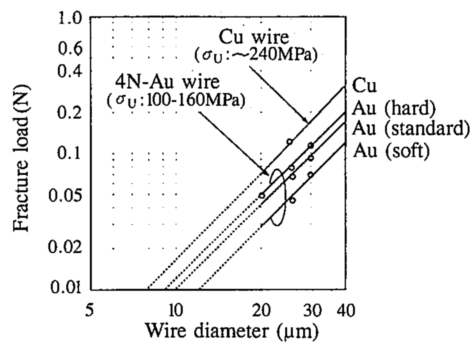


Fig. 3 Fracture load and tensile strength (σ_U) of simulated bonding wire HAZ

The bond strength of the gold wire/aluminum electrode interface is another important issue. When the ball is heated under pressure, the oxide film on the aluminum electrode surface is destroyed, exposeing a fresh surface. The resultant interdiffusion between the gold wire and aluminum electrode provides the desired bond strength. The bond strength is proportional to the area of the alloy phase formed by the interdiffusion and can be estimated from the bond area. The shear strength of the ball bond is about 100MPa under ordinary wire bonding conditions[2]. When the ball bond is heated at a high temperature for a long period of time, the interfacial strength is sharply reduced by the formation of Kirkendall voids. This failure may be countered by improving the wire bonding conditions. This is an important problem to be tackled in the future.

2.2 Laser beam welding of optical fiber cable metal protective tubes

Optical fiber cables are attracting attention as communication cables to support the information society. The optical fiber consists of a quartz-clad fiber core of about 0.1mm in diameter and a urethane-base organic coating of 0.4mm in diameter. Optical fibers may be used individually or may be bundled and covered with an organic material into a single cable. They are not suited for use as underground or submarine cables. Metal-sheathed optical fiber cables, or optical fibers encased in a metal tube, are developed and marketed under the tradename Picoloop by Nippon Steel Welding Products & Engineering Co., Ltd[3]. for use in sewer communication networks and other applications. Since the metal-sheathed optical fiber cables are produced by passing optical fibers through prefabricated metal tubes, they are limited in length. They must be joined into greater lengths to be laid with submarine power transmission cables, for example.

The stainless steel tube sheath (when made of type SUS304, for example) measures 1.5mm in outside diameter, 1.1mm in

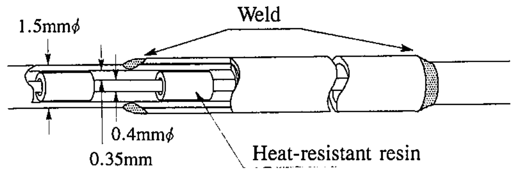


Fig. 4 Construction of metal tube weld joint

inside diameter, and 0.2mm in wall thickness. When optical fibers are passed through the tube, the clearance between the optical fiber bundle and the sheath inside wall is a mere 0.35 mm. The heat resistance of the organic coating is about 200°C instantaneously and about 60°C normally. The joining of the metal tubes calls for a precise joining technique with low heat input. A laser beam welding process was developed for this purpose[4]. Since any contact of the laser beam or plasma onto the metal tubes to be butt welded thermally damages the optical fibers, partial fillet fusion welding is adopted as shown in **Fig. 4**. When the metal tubes are continuously welded, the optical fibers are damaged by the heat radiated from the inside wall of each tube. Spot welds are made by a pulsed laser beam and locally overlapped to produce a continuous weld joint. For example, a spot weld with a diameter of 0.5mm and depth of penetration of about 0.3mm is made by a pulsed laser beam of about 30J. The inside surface of the tube just below the laser beam spot weld momentarily reached a temperature of nearly 600°C, and cooling the tube inside surface down to 200 and 100°C took 1.1 and 4.4 s, respectively.

Ideally, a heat insulating material should be preferably inserted in the tube, but its installation is restricted by a 0.35mm-clearance, and it may damage the optical fibers when the cable is used.

Finally, the optical fiber bundle was fixed at the central axis of the protective tube, an air layer was secured between the tube inside wall and the optical fiber bundle, and spot welds were repeated after long rest intervals to avoid damage to the optical fibers. The metal tube welds thus obtained were airtight, strong, failed the tensile test for base metal, and did not crack in the weld metal in collapse test.

3. Joining and Associated Technologies in the Aerospace Equipment Field

3.1 Repair of jet engine parts

High-pressure turbine (HTP) parts of jet engines, such as blades, vanes and duct segments, are used in extremely punishing environments, as shown in **Table 2**[5], and suffer various types of deterioration as they are used for long periods of time. Before these parts deteriorate and wear to an excessive degree, they are repaired to extend service life and reduce engine maintenance cost while assuring safety. Since these parts are the central compacts of jet engines, they have been long repaired only by engine manufacturers and a limited number of certified contractors.

In April 1988, Nippon Steel and Japan Air Lines jointly established Japan Turbine Technology as Japan's first company specializing in repair of jet engine HPT parts. The company was subsequently gained U.S. Federal Aviation Administration (FAA) certified cation as a parts repairer. The company has since increased the types of parts that can be repaired. To acquire various repair qualifications, Japan Turbine Technology has performed various forms of basic experiments on thermal spraying, joining and material technologies, and has verified the details involved. Some of these accomplishments are introduced here.

Table 2 Service environments of high-pressure turbine parts

Combustion gas	Maximum combustion chamber outlet temperature: 1220 to 1460°C Pressure ratio: 22 to 30 Trace amounts of harmful components in kerosene burned at rate of about 3 tons per second (during cruising) Oxygen in combustion air consumed at rate of about 150 tons per hour (during cruising), as well as dust, volcanic ash and seawater components
Temperature change	Rapid heating and cooling cycles in idle, takeoff, cruise, descent, and landing stages
Temperature gradient	Large temperature difference between inside with cooling air flow and outside in contact with combustion gas
Rotation (blades)	Moment at speed of 8,000 to 10,000 rpm Contact with duct segments

3.1.1 Transient liquid-phase (TLP) bonding

Vanes develop fine fatigue cracks after operating in extreme condition, as shown in **Photo 2**. These fine cracks produced by fatigue were formerly repaired by TIG welding. Recently, alternative repair techniques by transient liquid-phase (TLP) bonding, such as TURBOFIX™ and ADH (activated diffusion bonding), have been developed and commercialized[6].

TLP bonding consists of removing oxide and sulfide formed in the crack of the component by high-temperature reduction with hydrogen or hydrogen fluoride gas, applying filler metal to the surface of the crack, heating it in a furnace, and melting the filler metal into the crack. The filler metal is an alloy that contains boron as a melting-point depressant and is similar in composition to the base metal. When heated, the filler metal is melted at a temperature lower than the melting point of the base metal and introduced into the crack by interfacial tension. After the crack is filled with the filler metal, the component continues to be heated at a high temperature, causing the boron to diffuse into the base metal. As a result, the filler metal-filled crack region rises in average melting temperature and starts isothermal solidification, as evident from the results observed by high-temperature microscopy shown in **Photo 3**[7]. Mainting a high-temperature for a sufficient length of time helps the filler metal-filled crack region to acquire chemical composition and microstructure similar to that of the base metal and facilitates solidification.

Besides the above-mentioned metallurgical advantages, the TLP bonding method can process a large number of parts at a time, the operators require no special skills such as welding, and little thermal distortion results, among other things. With these characteristics, TLP bonding is replacing conventional repair welding.

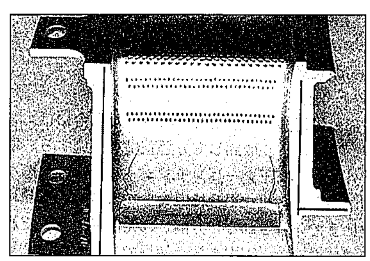
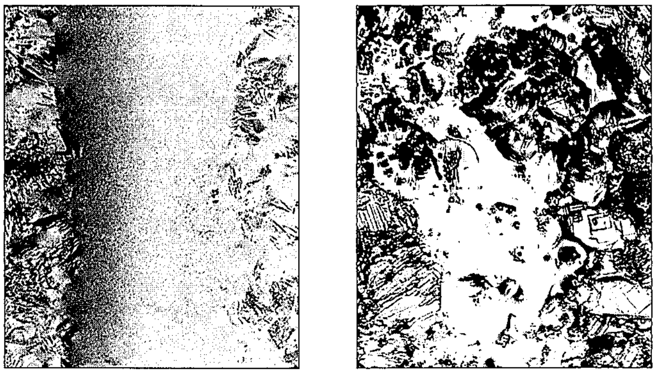


Photo 2 Cracks formed in vane after a few thousand hours of operation



(a) Initial (b) Middle

Photo 3 Observation of isothermal solidification by high-temperature microscopy

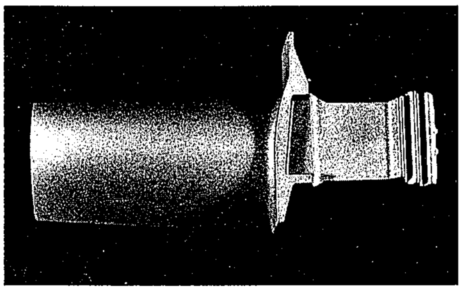


Photo 4 Low-pressure plasma sprayed blade

3.1.2 Thermal barrier coating plasma spraying

Jet engine parts subject to high temperatures must resist heat as well as oxidation. Thermal barrier coatings (TBCs) are applied to jet engine parts for protection against heat and oxidation. Aluminum is contained in the TBCs. An alumina film with excellent high-temperature oxidation resistance is formed while the engine is in service. As soon as the alumina film is removed by the thermal stress encountered, it reforms to protect the base metal.

TBCs are often applied by low-pressure plasma spraying (LPPS). Performed in a low-pressure argon atmosphere of a few tens of torr, LPPS can deposit TBCs of much higher cleanliness than atmospheric plasma spraying. The low-pressure inert atmosphere elongates the plasma, facilitates the melting of spray particles, and increases spray particle velocity, resulting in the formation of a tightly adhering thermal barrier coating.

A typical TBC formed by the LPPS process is MCrAlY (M stands for nickel or cobalt, or both). When compared with an aluminide coating applied by pack segmentation, the LPPS-deposited MCrAlY TBC is somewhat low in aluminum concentration, but is excellent in ductility, high-temperature oxidation resistance and wear resistance, and completely adheres to the base metal. **Photo 4** shows a blade with a low-pressure plasma sprayed TBC.

3.2 Development of functionally gradient materials of thermal stress relaxation type

Development of materials that can withstand the punishing thermal environment of space has become one of the important technological challenges for future space development. Functionally gradient materials (FGMs) with their composition

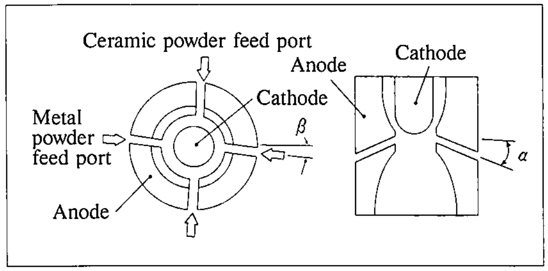


Fig. 5 Schematic showing four-port plasma spray gun

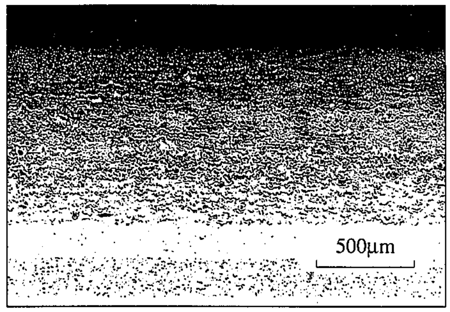


Photo 5 Macrograph showing section through zirconia/nickel alloy FGM coating

changing gradually (or continuously, if possible) in the direction of thickness were proposed as such materials[8]. Technology for forming the FGM with low-pressure plasma spraying (LPPS) has been under development[9].

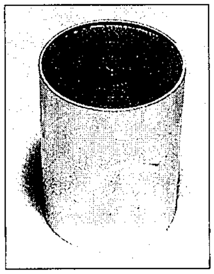
First, a single-gun mixing spray method (see **Fig. 5**) with a four-port spray gun was developed to separately feed ceramic and metal powders through independent lines to the spray gun and to mix them in a single plasma. Spray conditions in a medium-pressure region of 100 to 200 Torr were established to allow the melting of the high-melting point ceramic together with the metal. These achievements made it possible to form a uniform coating at any desired mixture ratio over a wide area without detracting from the basic LPPS advantage of depositing a clean, oxide-free coating over a wide area.

The section through an FGM formed from the combination of zirconia and a nickel-base alloy by the single-gun mixing spray method is shown in **Photo 5**. The FGM proved to have higher thermal shock resistance than conventional ceramic coatings in heat resistance testing by the combusting liquid hydrogen and liquid oxygen gas at the National Aerospace Laboratory, Science and Technology Agency[10]. The zirconia-nickel alloy FGM continues to be developed for use in the combustion chamber of an orbital maneuvering system (OMS) engine.

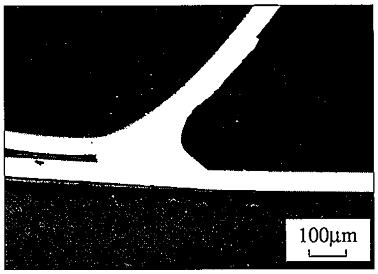
4. Joining Technology in the Automotive Field

4.1 Catalytic converter metal support

Metallic catalyst supports (metal supports) used in catalytic converters for cleaning automotive exhaust gases are superior to ceramic supports in such areas as weight reduction, conversion efficiency, and engine output[11]. The general view of a typical metal support structure is shown in **Photo 6**(a). Corrugated stainless steel foil and flat stainless steel foil are alternately lapped into a spiral honeycomb and inserted into a stainless steel jacket[12,13]. The corrugated and flat foils are each about 50μm in thickness



(a) General view



(b) Macrograph of honeycomb braze

Photo 6 Metal support

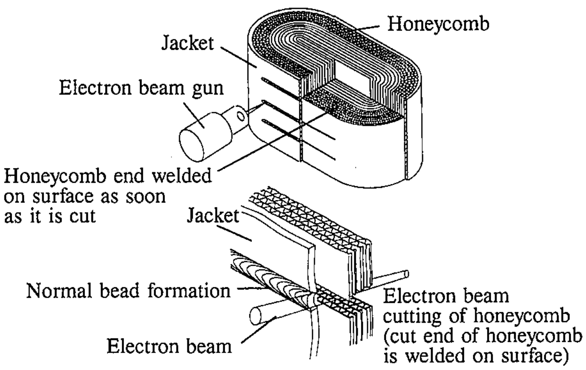


Fig. 6 Electron beam welding of metal honeycomb

and made of 20Cr-5Al ferritic stainless steel. A vacuum brazing process with the heat-resistant nickel-base filler metal BNi-5 (19Cr-10Si) was developed for joining the corrugated and flat stainless steel foils and securing the resultant honeycomb to the jacket[11-14].

Brazing produces area joints and is advantageous in that the workpiece can be simultaneously joined at as many points as required[12]. A new brazing process was developed that can achieve sufficient joint strength per point at high temperatures and minimize strength variability between the joint points. **Photo 6**(b) shows the section through a braze between corrugated and flat stainless steel foils. Since the metal catalytic converter is located close to the engine, the metal honeycomb must possess static high-temperature resistance and must be capable of withstanding the thermal stresses resulting from the thermal expansion and contraction due to the violent pulsation of hot exhaust gases. To meet this challenge, the arrangement of joints between the corrugated and flat foils and between the honeycomb and jacket was studied. As a result, a structure was developed that can reduce the thermal stresses produced axially and radially in the metal honeycomb. The metal honeycomb brazed in this way demonstrates high durability and is now used in automotive catalytic converters.

Research and development has also been carried out on metal supports joined by processes other than brazing. As shown in **Fig. 6**, irradiation of an electron beam from outside the jacket was found to simultaneously join the corrugated and flat foils in the honeycomb and the honeycomb and jacket. The metal honeycomb joined by this electron beam welding process has also met the above-mentioned performance targets[15,16].

4.2 Hardfacing of titanium alloy engine valves

Titanium alloys are used to make engine valves. Lighter than iron valves, they are expected to improve engine output performance. Conventional iron engine valves were hardfaced with Stellite by plasma arc powder welding as shown in **Fig. 7**. Because of cracking, the plasma arc powder welding process was not applicable to the Ti-6Al-4V titanium alloy. A new Co-Ti-6Al-4V hardfacing alloy was developed that features the same hardness range of Hv 450 to 650 as Stellite[17]. The hardfacing alloy produced by the rotating electrode process consists of spherical particles of about 200μm in size as shown in **Photo 7**, and stably performs when fed as powder. **Photo 8** shows the section through the hardfacing alloy deposited on the circumferential face of an engine valve. A hardfaced layer of uniform microstructure of about 1.5mm is obtained. This hardfacing alloy is expected to be used for increasing the wear resistance of titanium alloy parts.

4.3 Dissimilar-metal joining of steel and aluminum

Use of aluminum alloys is studied as a means for reducing

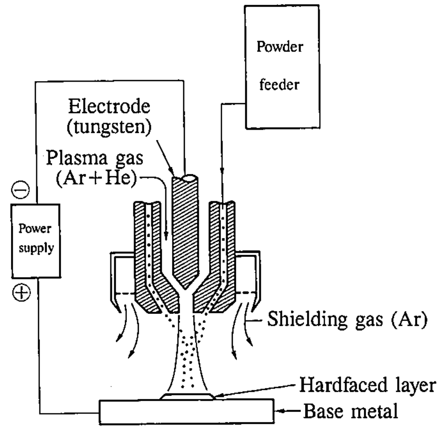


Fig. 7 Plasma transferred arc hardfacing process

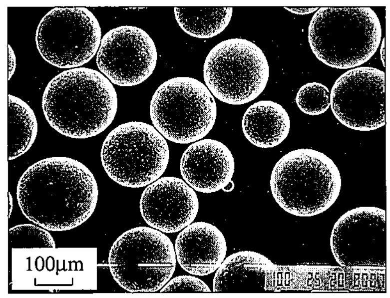


Photo 7 Hardfacing alloy powder (Co-Ti-6Al-4V)

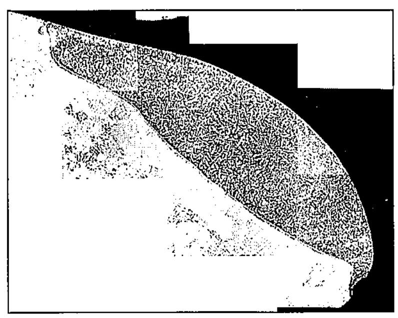


Photo 8 Section through hardfaced layer on circumferential face of engine valve made of titanium alloy

automobile weight. The applicable scope of aluminum alloys for this purpose is limited by material cost and properties, however. Reliable steel-aluminum joining technology will be necessary to increase the usage of weight-saving aluminum alloys in automobiles.

When steel and aluminum are directly welded, brittle intermetallic compounds form in the weld and make it impossible to obtain a good joint. The method of spot welding steel and aluminum sheets through inserting an aluminum-clad steel sheet has been studied as one solution to this problem. It has already proved effective with rolling stock and is expected to become a reliable steel-aluminum joining technology.

Nippon Steel developed the technology for manufacturing aluminum-clad steel sheets that feature high steel/aluminum interface bond strength and good formability[18]. This section introduces a steel-aluminum joining process that makes use of this technology[19].

Photo 9 shows the section through a steel-aluminum spot weld. Nuggets can be independently formed in the steel sheet and the aluminum sheet. An intermetallic compound layer of 2- to 5-μm thickness is formed at the steel/aluminum interface of the aluminum-clad steel sheet, and blowholes and cracks form in the aluminum sheet. These conditions do not reduce joint strength as described below.

Fig. 8 shows the effect of the welding current on the tensile shear strength (strength in the shear direction) and U-shaped tensile strength (strength in the peeling direction) of steel-aluminum welded joints. When an aluminum-clad steel sheet is used as the insert, the joint strength is higher than when steel and aluminum sheets are welded directly, and is approximately the same as when aluminum sheets are welded together. This is because fractures occur in the aluminum sheet. The available current range falls between that of steel-steel welds and that of aluminum-aluminum welds, probably because Joule's heating of the steel sheet encourages nugget formation in the aluminum sheet. Since the available current range is lower than when aluminum sheets are welded together, there is another advantage of electrode life (or number of spot welds that can be continuously made with a pair of electrodes) being longer than for welding of aluminum sheets.

Spot welding with aluminum-clad steel inserts produces high joint strength as discussed above and is expected to be a viable jointing process for automobile body parts of differing metals. Its practical application will call for clarification of fatigue strength, electrolytic corrosion and welding procedures, among other things.

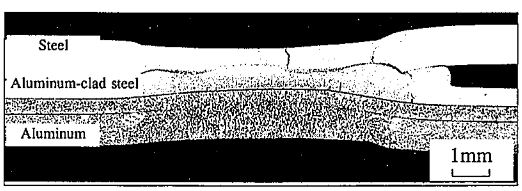


Photo 9 Cross-sectional structure of steel-aluminum spot weld (welding current: 10.8 kA, welding time: 0.2s)

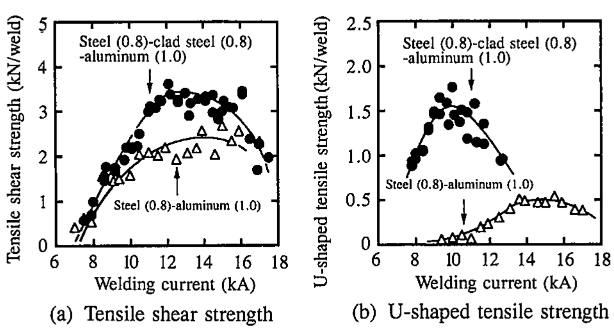


Fig. 8 Effect of welding current on joint strength (welding time: 0.2s, numbers in parentheses: thickness in mm)

5. Stud Welding Technology for Decorative Panels

When high-grade decorative steel sheets and stainless steel sheets, which are high in demand, are affixed to exterior and interior surfaces. Studs are often welded on the reverse side. The alteration, discoloration, and distortion of the top surface under the influence of stud welding heat must be minimized. A capacitor discharge stud welding (CDSW) process with low heat input and strain was developed to meet this challenge.

Among basic CDSW conditions are: 1) charging voltage; 2) polarity; 3) gun force; and 4) current waveform. After observation and analysis of the CDSW phenomena, an optimization control method was developed that suppresses the maximum current level and removes the unnecessary current components as shown

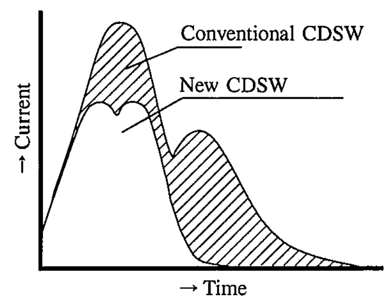


Fig. 9 Welding current optimization control

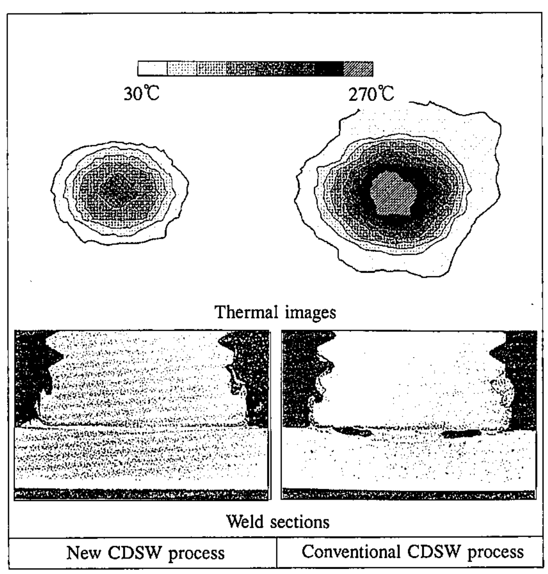


Fig. 10 Comparison of stud welds made by new and conventional CDSW processes

in **Fig. 9**. The steel sheet surface temperature distributions measured during CDSW cycles are shown in **Fig. 10**. This new CDSW process operates under a lower maximum temperature and a narrower heating range than the conventional CDSW process. As a result, high joint strength can be achieved, and prepainted steel sheets can be stud welded with a minimum of adverse thermal effect and thermal strain, and without damage to the decorative surface.

6. New Thermal Spraying Technology for Ironmaking and Steelmaking Facilities

Iron and steel making facilities are subject to severe deterioration and damage, such as wear and thermal shock damage, and are protected by such surface modification techniques as plating and thermal spraying. **Table 3** summarizes the thermal spraying techniques currently applied to iron and steel making facilities. Thermal spraying is advantageous over plating as it offers a wider selection of coating materials and heavy coating thickness. On the other hand, thermal spray coatings are generally low in impact strength and likely to peel at the interface. These problems have led to calls for the development of thermal spraying technology that can deposit high-quality coatings. Against this background, new thermal spraying processes, or low-pressure plasma spraying (LPPS) and hybrid plasma spraying, have been studied for application to iron and steel making facilities.

A thermal spraying process that has been mainly applied to jet engine parts, low-pressure plasma spraying (LPPS) can deposit smooth superalloy coatings. **Photo 10** shows a horizontal continuous casting copper mold LPPS coated with the Mar-M 509 alloy, a cobalt-base superalloy that has relatively excellent thermal shock resistance and good zinc penetration resistance. In this example, a heat-resistant plasma spray coating is formed on the inside surface of a severely damaged mold inlet. The coating has proved to be effective in preventing high-temperature damage of the copper mold as well as the cold shut cracking of the cast piece due to its heat insulating effect.

Hybrid plasma spraying is a new thermal spraying process that combines two types of plasmas, or direct-current plasma and alternating-current (or radio-frequency) plasma as shown in **Fig.11**. It can effectively heat spray particles and thus can use large spray particles. The combined use of the DC and RF plasmas and the optimization of particle diameter can deposit coatings with excellent coating strength and interfacial strength. It is now under development as to small parts applications, such as hot extrusion dies as shown in **Photo 11**.

Table 3 Thermal spraying applications in iron and steel making facilities

		Spraying material	Purpose
Raw material treating plants	Hoppers, chute liners, coke and sinter grizzly bars	Ni-base self-fluxing alloy	Wear resistance
Blast furnaces	Tuyeres, charging appliance seals	Ni-Cr and ZrO_2 self-fluxing alloys	Wear resistance, heat resistance
LD converters	Lance tuyeres	ZrO_2	Heat resistance
Continuous casters	Molds, guide liners	Ni-base self-fluxing alloy, WC-Co	Wear resistance, heat resistance
Hot rolling mills	Transfer rolls	Ni-base self-fluxing alloy	Wear resistance, seizure resistance
	Rolling rolls	Ni-base self-fluxing alloy	Wear resistance, heat resistance
	Guide rolls, side guides	Cr_3C_2-NiCr	Wear resistance, seizure resistance
Cold rolling mills	Hearth rolls	Cr_3C_2-NiCr	Seizure resistance
Coating lines	Line top rolls	WC-Co	Wear resistance, deposit resistance
	Sink rolls, support rolls	Ni-base self-fluxing alloy	Corrosion resistance

Photo 10 General view of horizontal-cast copper mold LPPS coated with Mar-M 509 alloy

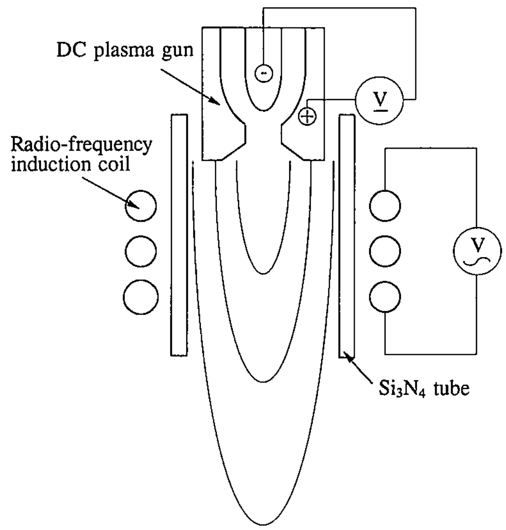


Fig. 11 Schematic showing hybrid plasma spraying process

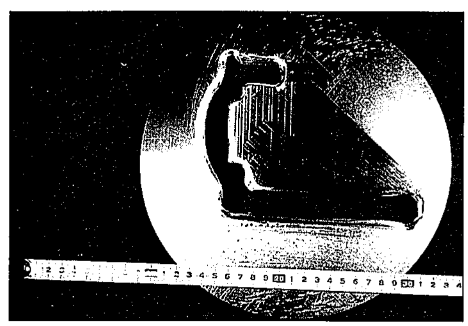


Photo 11 Heat-resistant coating applied to hot extrusion die by hybrid plasma spraying process

7. Conclusions

Some of the joining technology developments for new application fields and products have been introduced above. Since the materials and parts addressed here must perform their characteristic functions, they call for peculiar approaches in analyzing the phenomena involved and evaluating the properties of joints made. The pursuit and development of these technologies has also been carried out as principal research subjects, but they have been very briefly mentioned here because of limited space.

As Nippon Steel enters many more new businesses, joining will assume increasing importance as a key technology. We will accumulate findings obtained with respect to specific subjects and will forge ahead with new technological developments.

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