NIPPON STEEL TECHNICAL REPORT No. 65 APRIL 1995

UDC621.791:669.14 - 415

Welding Technology for Uncoated and Coated Steel Sheets for Automobiles, Household Electric Appliances, and Containers

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Abstract:

A variety of welding technology is used to join steel sheets in the automobile, household electric appliance, and beverage container industries. The weldability of steel sheets used in these applications is evaluated by viewpoints and techniques characteristic of specific steel-welding process combinations. Basic findings are described on the evaluation of resistance spot weldability of various types of high-strength steel sheets, coated steel sheets, and vibration damping steel sheets. Recent findings are reported on welding phenomena and weldability governing factors associated with the flash welding and upset welding of wheel rims and the mash seam welding of containers. Laser beam welding for tailored blanks is outlined, and laser beam welding conditions, laser beam weld formability and their evaluation techniques are introduced.

1. Introduction

In automobile, household electric appliance, beverage can, building material and other steel sheet application fields, improvements in performance properties such as safety, lightness of weight, durability, design and comfort were pursued after the economic boom era to achieve higher productivity and lower cost. These challenges were met by the development of various types of high-strength steels and coated steels as well as vibration damping steel, a new functional product. A new welding process, direct-current (DC) butt welding, and a new production technology, tailored blanks, also made their debut. These trends accelerated many efforts to develop new techniques of steel weldability and weldability evaluation, and new welding processes.

Many of there projects began with a clarification of the phenomena inherent in individual welding processes. Today, weldability research results are reflected in many commercial steels, weldability evaluation techniques are clearly positioned and commonly shared, and several proposals for other welding technologies have been advanced. Some of the major technologies are introduced here.

2. Resistance Welding of Automotive Steel Sheets

In the automotive steel sheet area, high-strength sheets to enhance body safety and weight reduction and coated sheets to improve corrosion resistance have appeared and been refined since the late 1970s. Resistance spot welding is still the primary welding process for automotive body assembly. Recent years have seen the accelerating use of new welding processes, laser welding and arc welding for body and underbody parts, and DC

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but welding for wheels.

2.1 Spot welding

In spot welding, it is important to know and evaluate the effect of steel chemical composition on the strength of welds in high-strength steel sheets and to prolong electrode life for coated steel sheets.

2.1.1 High-strength steel sheets

The following empirical equations are derived for the tensile shear strength (TSS) and cross-tension strength (CTS) in the peeling direction of spot welds[1]:

$$TSS = A \cdot Dn \cdot t \cdot TS \quad \cdots\cdots(1)$$

$$CTS = B \cdot Dn \cdot t \quad \cdots\cdots(2)$$

where Dn = nugget diameter; t = sheet thickness; TS = tensile strength of base metal; A and B = proportionality constants. These equations show that achievement of the desired nugget diameter is basic to assure the specified strength of a weld. It should be noted that the strength of a spot weld in the peeling direction does not depend on the strength of the base metal and declines to a greater extent when a fracture occurs inside a nugget than when one occurs outside of a nugget as expressed by Eq. (2)[1]. Since the fracture in-nugget is related to the chemical composition of the steel sheets, the relationship between the alloying elements and the fracture mode was studied with respect to rephosphorized steel sheets of 0.8 mm thickness (see **Fig. 1**). The following empirical equation indicates the compositional limit for the conventional hold time T_h of 25 cycles:

$$C + Si/30 + Mn/20 + 2P + 4S \leq 0.24(\%) \quad \cdots\cdots(3)$$

This points to the involvement of the hardening of spot welds. Since the increase in sheet thickness and the decrease in electrode hold time decrease the cooling rate after welding, it is natural that they should also alleviate the compositional limit[2]. The effect of the hold time can clearly be seen in **Fig. 1**. When T_h = 5 cycles, the compositional limit is 0.31%. **Fig. 1** shows the results of a field peel test which is a current method on the production line. Verification of the correlation between the peel test and the crross- and U-tension tests confirmed the validity of the peel test.

2.1.2 Coated steel sheets

Coating metals are generally soft materials with a low melting point. The currect path is therefore greater both between electrode and sheet and between sheets in spot welding of coated materials than uncoated, which in turn calls for higher current, longer weld time, and higher heat input[3-4]. As the coating weight increases, the weldable current range shifts toward higher current, narrows in width, and reveals the effect of the coating type, as shown in **Fig. 2**. Coupled with this requirement of high weld current and long weld time, the alloying of the electrode copper with the coating metal accelerates wear on the electrode and shortens its life. The electrode life expressed by the number of spot welds that can be made continuously with the electrode decreases with increasing coating weight for both type CF and type R electrode shapes, as shown in **Fig. 2**. Electrode life is basically governed by the electrode wear rate, but two peculiar phenomena were also found to govern the electrode life[5].

Electrode faces worn convex, concave, or flat have been observed; electrode life is influenced by this electrode face wear pattern. **Fig. 3** compares galvannealed steel sheets (45/45g/m²) and electrogalvanized steel sheets (20/20g/m²) and electrode life N_b is $N_b \geq$ 6,000 welds and N_b = 1,500 welds, respectively. This

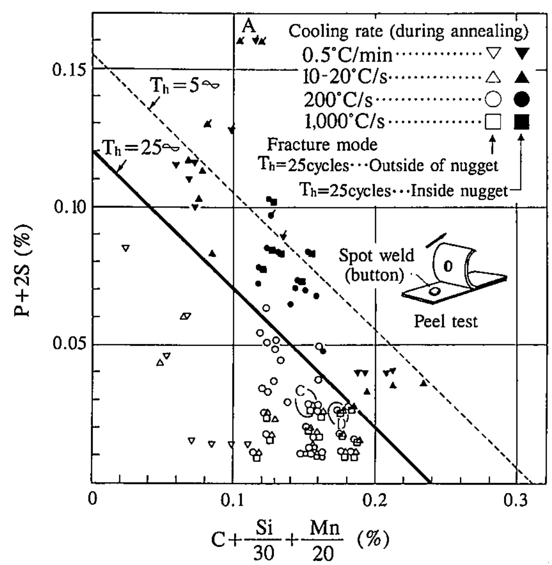


Fig. 1 Effect of steel chemical composition on fracture mode in peel test

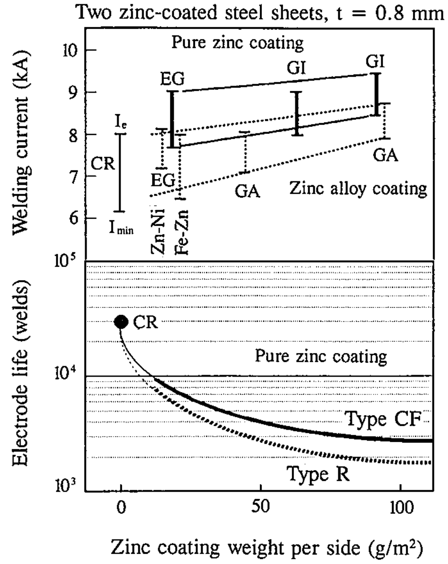


Fig. 2 Effect of zinc coating weight on available current range and electrode life

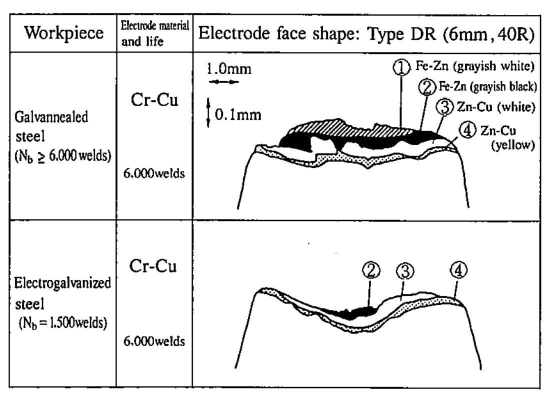


Fig. 3 Electrode face shape and cross-sectional alloy layer composition after welding

is because the electrode face wear pattern is convex for the galvannealed steel and concave for the electrogalvanized steel. The electrode face is worn by about 0.1mm at most. The convex wear pattern involves a smaller drop in the current density and thus has a more favorable effect on the electrode life. The galvannealed steel forms an iron-zinc alloy layer on the electrode face, but the formation of this layer is very small for the electrogalvanized steel. The mechanism governing the phenomenon of the variation in electrode life with the electrode face wear pattern is not yet fully understood and will have to be studied further.

When the weld lobe (weldable current range) is compared before and after electrode wear, the electrode life correlates well with the current margin ΔI for electrogalvanized steel as shown in **Fig. 4**. The current margin ΔI is defined as the difference between the evaluation current of welding in an electrode life test with initial electrodes, I_b, and the minimum current required for nugget formation with the electrode of an enlarged contact area, I_0. This phenomenon of electrode life being governed by the weld lobe is found to be related to the electric contact resistance of the coating surface and suggests that coating surface conditions like oxide film have an important effect on electrode life.

Electrode wear is one of the most fundamental problems in resistance spot welding. Many electrode materials, composite electrodes, and electrode face treating techniques have been proposed as improvements in this process in relation to the steel research and development results discussed above, but they have not been practically applied following a comprehensive evaluation of their simplicity, applicable range, benefit, cost, and other factors.

Against this background, Nippon Steel has developed and proposed the spin electrode process[6]. A general view of the spin electrode equipment is shown in **Photo 1**. As shown in **Fig. 5**, this process inclines the upper and lower electrodes by the angle θ normal to the steel sheet surface, rotates them for the angle α after a given number of spot welds, and sequentially moves the electrode face that contacts the steel sheet. When θ = 10° and α = 60°, the spin electrodes were confirmed to last about 20 times longer than conventional resistance spot welding electrodes when used for resistance spot weld galvannealed, electrogalvanized, or thin-film organic composite-coated steel sheets singly or in combination. This is also true for aluminum alloy sheets. The spin electrode process is applicable to robots and guns and is expected to find widespread use.

2.2 Flash welding and DC butt welding of wheel rims

Passenger car wheels are fabricated by welding disks to cylindrical rims. Hot-rolled steel blanks, each measuring about 3mm thick, 200mm wide, and 1000mm long, are welded into cylindrical form and roll-formed to produce about 10 wheel rims per minute. The rims are welded by conventional flash welding and the recently developed DC butt welding process.

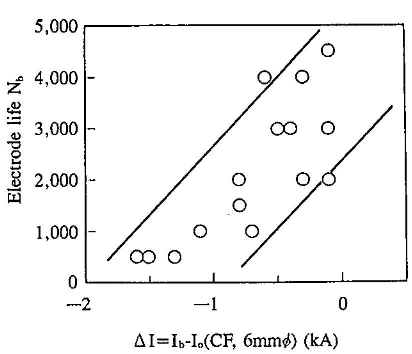


Fig. 4 Effect of current margin on electrode life

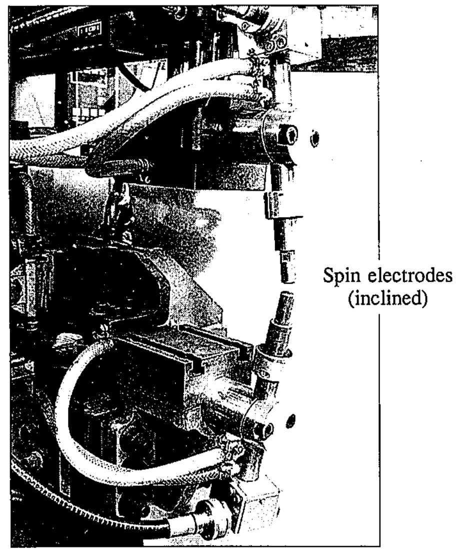


Photo 1 General view of spin electrodes

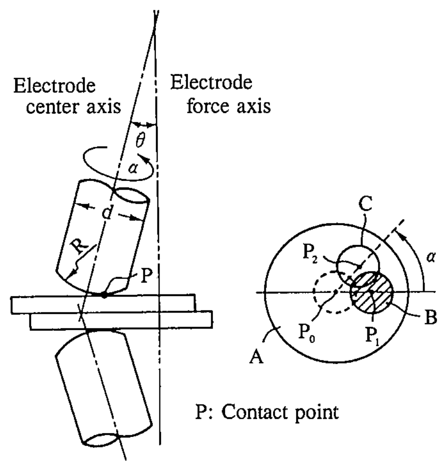


Fig. 5 Operating principle of spin electrode process

The flash welding process forms a welded joint in two stages: the initial flashing stage and the subsequent upsetting stage. In the flashing stage, a cylindrical workpiece is lightly abutted edge to edge, locally short circuited, supplied with arcing current, and heated by the Joule heat and arc. The weld is completed by applying pressure in the upsetting stage. A flash weld takes about 2 to 3s to complete. High in productivity, the flash welding process has been used in wheel rim fabrication.

When high-strength steel sheets were used to fabricate wheels to meet the weight reduction of automobiles about 1970, cracking at the weld interface became a problem in the forming step after welding. Scanning electron microscopy (SEM) revealed the presence of composite oxides (penetrators), such as those of silicon and aluminum, on fracture surfaces (see **Photo 2**). These penetrators were shown to initiate the cracking of the flash weld interface during forming. It was learned that the penetrators are

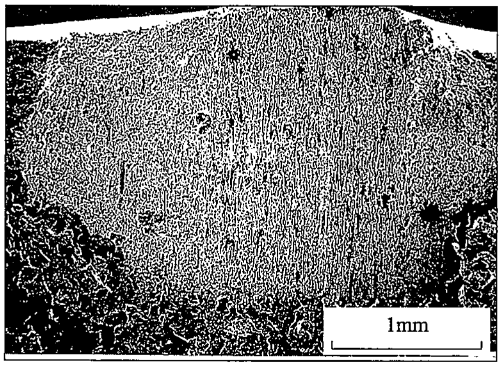


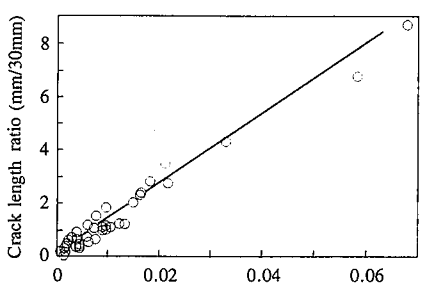
Photo 2 Example of fracture surface at weld interface in bend test

derived from the composite oxides formed at the edges in the flashing stage, so the effect of steel composition was studied. An equivalent formula (F_{eq}) was derived to indicate the effect of steel composition on weld interface crack length ratio and was used as a guideline for material design and selection (see **Fig. 6**). As a result, a high-strength niobium-microalloyed steel sheet with a tensile strength of 60kgf/mm^2 was commercialized and established as a material for fabrication of wheel rims with higher strength[7].

After analysis of the welding phenomena involved, process control and upset timing control technology were developed to reduce weld interface defects[8]. The latter technology computes the flashing current in real time and relative to the irregular flashing phenomenon, and determines the best timing to go to the upsetting stage. It was proposed as an effective means for flash welding steel sheets likely to have their edges oxidized in the flashing stage.

In the 1980s, upset welding by direct current or DC butt welding was investigated for application to wheel rim fabrication. The DC butt welding process abuts members end to end, applies force to the joint, heats and softens the joint by the Joule heat produced by short-circuit current, and welds the joint in the solid state. It is advantageous in that the welding time is short, about 1s, and the equipment and product are not contaminated by a flash. In the past, this welding process was applied only to relatively small sections and not to members that must be highly reliable. Its application to high-strength steel sheets was particularly doubted.

The DC butt welding process was found to increase joint



$F_{eq} = (C-0.03)(Si^2+(Mn/10)^2+(3Al)^2+(3Cr/2)^2)$

Fig. 6 Determination of weld interface crack length by weldability equivalent formula (F_{eq})

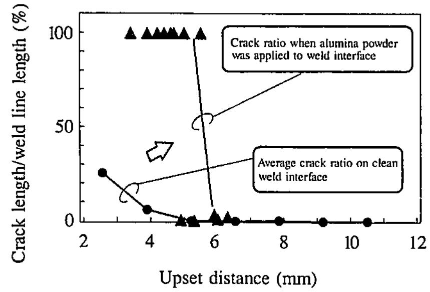


Fig. 7 Effect of upset distance on weld interface crack ratio

strength by increasing the upset. Expanding the weld interface by increasing the upset is the key (see **Fig. 7**)[9]. This means that cleaning of the weld interface by dispersion and size reduction of oxide inclusions during expansion of the interface promotes solid-state welding of the butt joint. Welding conditions which raise temperature of the weld interface and increase its expansion should be selected. In other words, it is effective to make positive use of the contact resistance between the faying surfaces under a lower pressure of about 10kgf/mm^2, to minimize the heat conduction loss by passing the weld current at a higher current density of about 150A/mm^2, and to form a steep temperature distribution peaking at the contact point between the faying surfaces. To perform stable welding under these conditions, the faying surfaces must be cut extremely straight. With the welding of sheet shapes like wheel rims, partial melting of the contact area is unavoidable. Complex oxides similar to the penetrators formed in flash welding were identified in the contact area. This suggests that material design based on the above-mentioned equivalent formula F_{eq} is also valid for the DC butt welding process. This process is now applied to high-strength steel sheets up to 60-kgf/mm^2 class in the production line.

3. Welding of Vibration Damping Steel Sheets[10]

Vibration damping steel sheets are used for noise abatement. This is a composite structure with a visco-elastic resin (damping resin) of 40 to 100μm thickness sandwiched between two steel sheets. They are used in automobiles, electric household appliances, industrial machinery, building materials, and many other areas.

Vibration damping steel sheets are usually welded by resistance welding like spot welding. Damping resin is a good insulator and cannot establish a current path under electrode force alone. These conditions have made resistance weld of vibration damping steel sheets impossible, but development of subsequent technology and material improvement enabled this to be done successfully. A bypass circuit welding method that makes use of the nature of damping resin softening under heat was developed and applied; this is used for parts (such as oil pans) with a relatively small number of spot welds.

Vibration damping steel sheets of the direct conducting type that make the damping resin electrically conductive by filling it with stainless steel or nickel particles are used to fabricate mass-production parts with a larger number of spot welds. **Fig. 8** shows the effect of the weld current on the nugget diameter when a direct-conducting type vibration damping steel sheet or cold-rolled steel sheet is resistance spot welded to another cold-rolled steel sheet of the same thickness. Since the direct-conducting type

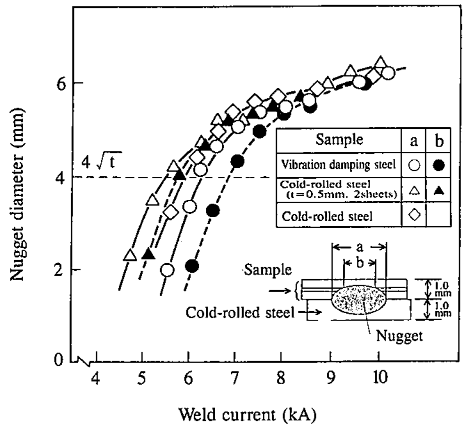


Fig. 8 Effect of weld current on nugget diameter

vibration damping steel sheel takes some time to expel the damping resin, the weld current required to obtain the same nugget diameter is higher than for the cold-rolled steel sheet pair at the low end of the available current range. At the high end of 8kA or more, the direct-conducting type vibration damping steel sheet has the same nugget diameter as the cold-rolled steel and equivalent weld strength.

Use of appropriate material impart the same weldability as conventional cold-rolled steel sheets to vibration damping steel sheets of the direct conducting type. In addition, welding procedure measures, such as step-up current application and upslope current application, are effective in obtaining stable spot weldability in actual production runs.

Besides resistance spot welding, there are appropriate conditions for other resistance welding processes, such as projection welding of nuts and stud welding of bolts for attaching parts, and for arc welding and arc spot welding.

4. Laser Welding of Tailored Blanks

The technology of assembling individually formed parts by welding and that of forming large single blanks were traditionally used in the manufacture of automobile bodies. The former provides a high material yield and allows the right materials to be used for the right strength or corrosion applications for parts by parts, while the latter provides good part appearance or stiffness and allows reduction of the necessary quantity of press tooling and welding equipment. The tailored blank technology of joining blanks and forming them into one-piece parts was developed to combine the advantages of these two conventional procedures and is finding widespread use in automobile body manufacturing[11].

Tailored blanks technology call for high-efficiency welding process. At the same time, problems associated with the press forming of steel blanks that contain welds of different mechanical properties or sheets of different thickness or strength must be overcome[12,13]. Selection of appropriate steels and welding conditions is important in this respect. At present, laser beam welding and mash seam welding are the tailored blank welding processes used for specific applications. Laser beam welding is described below.

Laser welding uses a heat source of high energy density. This density reduces the weld bead width and minimizes the range of mechanical property changes caused by welding, while its high cooling rate hardens the weld. The hardening degree of the weld

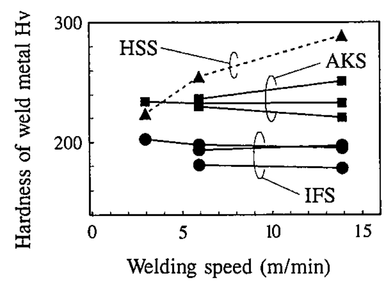


Fig. 9 Effect of welding speed on hardness of weld metal

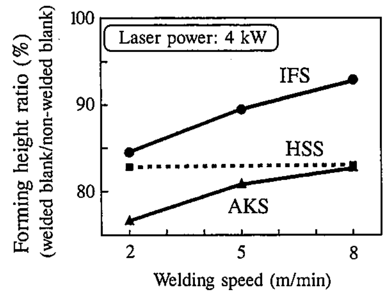


Fig. 10 Effect of welding speed in Erichsen test (tailored blanks welded of sheets of same type of steel)

metal is governed by the carbon content of steel and cooling rate. As shown in **Fig. 9**, low-hardenability ultralow-carbon titanium-microalloyed steel [or interstitial-free steel (IFS)] can reduce the maximum hardness of the weld more than low-carbon aluminum-killed steel (AKS) or rephosphorized high-strength steel (HSS). When IFS and AKS are laser welded with a power of about 4kW, their hardness of welds depend little on the welding speed within the practical range of 3 to 10 m/min.

Formability of tailored blanks can be approximately evaluated by the Erichsen test and hydraulic bulging test. When tailored blanks are laser beam welded from sheets of the same type of steel as shown in **Fig. 10**, they fracture across weld beads. The forming height of the IFS and AKS tailored blanks increases as the weld bead width decreases with greater welding speed. In contrast, the forming height of the HSS tailored blanks does not increase as much with increasing welding speed. This forming height is believed to depend on both weld bead width and hardness. For the HSS tailored blanks, the decrease in weld bead width and increase in hardness are thought to cancel each other. When a tailored blank fractures across a weld bead, its forming limit is governed by the fracture limit strain of the weld metal which is lower than that of the base metal.

The forming height of tailored blanks welded from different type steel sheets falls between that of the component steel sheets, as shown in **Fig. 11**. Even when a narrow weld bead is formed by welding at high speed, the concentration of strain in the lower-strength steel sheet causes the fracture of the base metal along the weld bead and does not improve the forming height. In this case, the formability of the tailored blank is thought to be governed by the strength balance between the portions crossing the weld bead.

Laser welding involves a small amount of melting. Any gap between the faying surfaces of a joint sharply reduces the weld

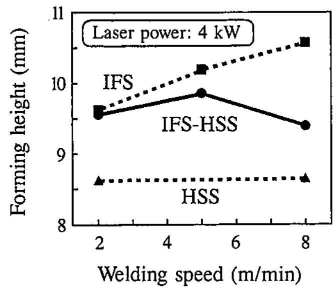


Fig. 11 Effect of welding speed in Erichsen test (tailored blanks welded of sheets of different types of steels)

bead thickness. When the bead thickness is less than 70% of the base metal thickness, the tailored blank fractures at the center of the bead and declines greatly in formability. Use of filler wire is effective in preventing the weld bead thickness from decreasing. Since carbon in the filler affects the hardness of the weld metal, selection of a low-carbon filler is necessary, especially for IFS.

Cracks caused in tailored blanks in the Erichsen test are either transverse cracks at right angles to the weld bead or longitudinal cracks along the bead. Attempts have been made to classify and arrange these tailored blank forming cracks by a constant-strain model and a constant-load model[14]. The tailored blank technology is expected to find increasing use in applications other than automobiles.

5. High-Speed Mash Seam Welding of Can Materials

Steel cans for beverages, foods, paints, fuels, chemicals, and cosmetics are in increasing use today. Three-piece cans consist of a body, a top and a bottom. Body seams are joined by welding, cementing, or soldering. Welded cans are characterized by small steel consumption and high productivity.

Resistance mash seam welding is the process chiefly employed for three-piece cans. Since a fresh copper wire is used only once as an intermediate electrode between the copper electrode and steel sheet as shown in **Fig. 12**, resistance mash seam welding can be performed stably and well without electrode contamination. This process can weld 600 cans per minute (at a speed of 50m/min) from sheets about 0.2mm in thickness. The seam weld can be mashed to an overthickness about 1.4 times the single sheet thickness by finely adjusting the seam overlap to about 0.4mm. This means that can edges can be formed almost uniformly.

The longitudinal section of a mash seam weld in the weld line direction in tinplate sheets is shown in **Photo 3**. The way one nugget is formed for each half cycle of the weld current is obvious. Mash seam welds in beverage cans in which gas-tightness is of the greatest importance must be tight and continuous and must have a minimum of inner surface metal splash in terms of corrosion resistance and repair lacquerability. Mash seam weldability refers to the available current range from the lower limit at which a strong enough weld is made to the upper limit at which metal splash is caused.

As shown in **Fig. 13**, mash seam weldability can be approximately determined by electric contact resistance[15]. When steel sheets have a low contact resistance like those of tinplate, the current path through the sheets between the electrode wheels is wide as shown in **Fig. 14**(a), so that heat is extensively generated over the weld interface to facilitate the formation of continuous nuggets. When steel sheets have a higher contact resistance as do TFS-CT (chromium-type tin-free steel), the current path is redistricted as shown in **Fig. 14**(b), so that heat is locally generated over the weld interface to facilitate the growth of nuggets in the

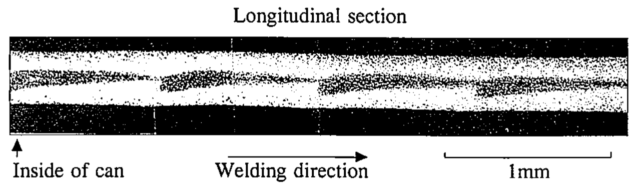


Photo 3 Weld section (#10 tinplate)

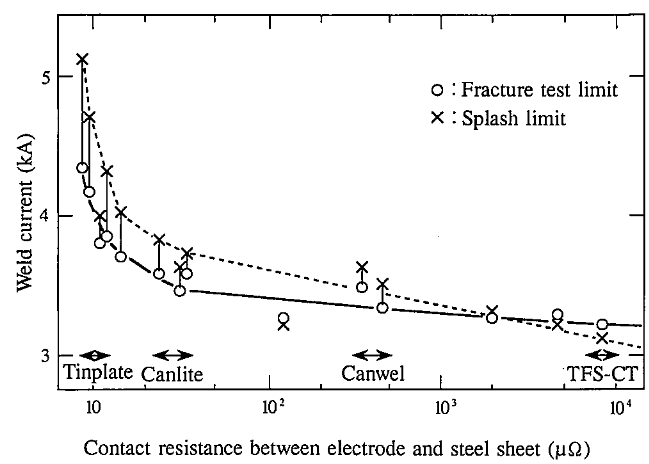


Fig. 13 Contact resistance versus weld current range

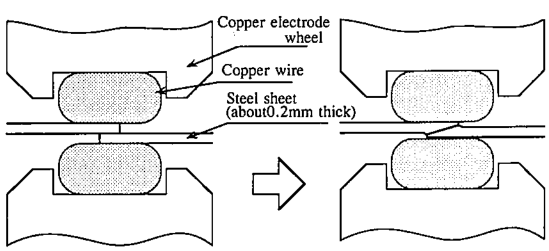


Fig. 12 Wire seam welding process

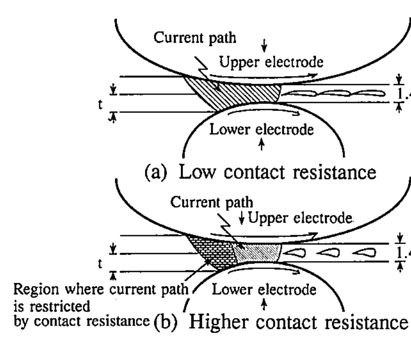


Fig. 14 Schematic showing current path

Table 1 Mash seam weld test methods

Material	Test	Weld current (arbitrary unit) (Start of nugget formation 1.0 — 1.1 — 1.2 — 1.3)
Tinplate #10	Pull-off test θ=30°	× × ××○○○ ○ ○ ○ ○○○ ○
	Pull-off test θ=45°	× × ×○○○○ ○ ○ ○ ○○○ ○
	Roll-back test	× ○ ○○○○○ ○ ○ ○ ○○○ ○
	Conical test	△ ○ ○○○○○ ○ ○ ○ ○○○ ○
	Visual test	○ ○ ○○○△○ ○ ▽ △ △△△ ×
Canwel	Pull-off test θ=30°	×× × ×○ ○ ○○
	Pull-off test θ=45°	×○ ○ ○○ ○ ○○
	Roll-back test	○△ ○ ○○ ○ ○○
	Conical test	×○ ○ ○○ ○ ○○
	Visual test	○○ ○ ○○ △ ××
TFS-CT	Pull-off test θ=30°	× × × × × × × ×× ×× ×××○ ×○ ○
	Pull-off test θ=45°	× × × × × × × ×○ ○× ○×○○ ○○ ○
	Roll-back test	○ × △ ○ ○ ○ ○ ○○ ○○ ○○○○ ○○ ○
	Conical test	× × × ○ △ × ○ ○△ ○△ ○○○○ ○○ ○
	Visual test	○ ○ ○ ○ ○ ○ ○ △○ △△ △△×× ×× ×

Criterion	○	△	×
Pull-off test	Accepted	…	Fractured
Roll-back test	Accepted	Peeled over 3mm or less	Peeled
Conical test	Fractured in base metal	Mixed	Peeled in weld
Visual test	Good	Slight splash (▽: Reject)	Extensive splash

thickness direction and the occurrence of metal splash, making it difficult to ensure nugget continuity. This problem prompted research on new types of coated steels featuring excellent mash seam weldability and relatively low contact resistance. A nickel-coated steel designated Canwel and a nickel-preplated lightly tin-coated steel designated Canlite, were coated steel products developed for beverage cans, each combining corrosion resistance and weldability[16].

Mash seam welds are evaluated by a variety of test methods, although there is no standardized method. Pull-off test (tear test) is a common method, and there is also a roll-back test (flange bend test) and a conical test (expansion test). Weld strength and peel strength are evaluated, among other properties. **Table 1** gives the comparative results of these mash seam weld test methods. Judgment of the available current range varies with the method employed, with the pull-off test being most severe. Whether or not the pull-off test can really simulate the actual functional performance of beverage cans, however, has not been confirmed, and these test methods must be studied further.

Welded can steels must meet requirements of ever increasing severity, as represented by downgauging and welding speed increase to 100m/min, and must also be lower in cost. It is also urgent that welding techniques for TFS-CT and other non-weldable materials be developed.

6. Conclusions

Major developments in welding technology for uncoated and coated steel sheets over the past few years have been outlined and described. Uncoated and coated steel sheets cover a wide range of applications and are welded by a variety of processes. Many of the products made from these sheets are mass-produced to exact quality tolerance levels. Thus, welding, along with steel development, must meet various requirements as one of the key technologies influencing cost and quality. It is hoped that welding technology will further progress and solve the problems described here as well as new ones that may arise in the future.

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