Abridged version

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Spot-Weldable Vibration-Damping Composite Sheet Steel "NONVIBRA"

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Synopsis :
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Spot-Weldable Vibration-Damping Composite Sheet Steel "NONVIBRA"*1

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Toshio IRIE*5 Yukio FURUKAWA*6 Junsuke TAKASAKI*7

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1 Introduction

Many grades of sheet steels are used for automobiles. Taking cold-rolled sheet steels as an example, seven grades in all: drawing quality (DQ) steel, deep drawing quality (DDQ) steel, extra deep drawing quality (EDDQ) steel, rephosphorized steel, dual phase steel, precipitation hardened steel, and ultra high-strength steel are used for this purpose. If hot-rolled sheet steels and surface-coated sheet steels are added thereto, no less than twenty grades of sheet steels are used for meeting the requirements.

Recently, demand for vibration-damping sheet steel has increased from the needs of automobile noise control and improved habitability of the automobile cabin. Namely, development has been demanded for sheet steel which has similar mechanical properties to those of the above-mentioned automotive sheet steels and also has outstanding vibration-damping quality. Such needs came not only form the automotive industry but also from other fields such as home electrical alliances, industrial machinery, OA equipment, shipbuilding and bridge construction. To meet such needs, Kawasaki Steel has developed vibration-damping composite sheet steel **(NONVIBRA)** in which a viscoelastic resin layer is sandwiched by steel-sheet skin layers, and also has developed lightweight composite sheet steel **(RIVER LAMINATE)** which has similar construction to that of NONVIBRA, but is different in kinds and thickness of resin. Both of them are given a generic name of "composite sheet steel." Major differences between them are shown in **Fig. 1** and **Table 1**.

Compared with conventional vibration-damping alloys[1] of twin type, dislocation type, or ferromagnetic type, the vibration-damping composite sheet steel excels in vibration-damping quality which is important in this grade of steel, and thus can be used as the most desirable vibration-damping material. Also a comparison between the vibration-damping composite sheet steel and conventional sheet steel is given in **Table 2**. Namely, the vibration damping property of the vibration-damping composite sheet steel is 10^2 to 10^3 higher than that of

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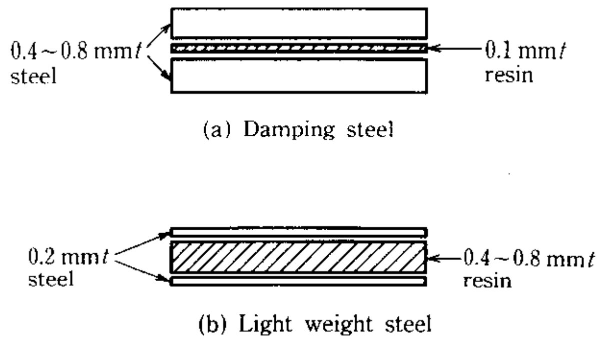


Fig. 1 Two types of composite sheet steels

Table 1 Differences between two types of composite sheet steels

	NONVIBRA	RIVER LAMINATE
Object	Vibration damping	Weight reduction
Resin	Viscoelastic	Thermoplastic
Ply-ratio	$\leqq 0.2$	$\geqq 0.5$

Table 2 Properties of conventional composite damping sheet steels

Property	Characteristic compared with SPCE
Damping ability	$10^2 \sim 10^3$ higher
Tensile property	Almost the same
Formability	Almost the same except that wrinkles are apt to occur
Spot weldability	Very poor

conventional sheet steel, and mechanical properties of these two steels are almost the same. There is no problem in heat resistance, because the vibration-damping composite sheet steel can withstand the paint bake treatment which it receives in the manufacturing process of automobiles, but in the spot weldability, vibration-damping composite sheet steel which was developed in the past is inferior in workability to conventional sheet steel. This is because the resin in the intermediate layer inherently lacks electric conductivity, direct spot welding is impossible by the conventional method. To correct these defects, various methods have been proposed or executed, such as installing a bypass cicuit[2], providing a subsidiary electrode[3], and the punch mark method.[4] These methods have made spot welding possible, but they have caused elongation of welding time, increased instability of weld quality and a rise in cost, and have proved that they are not the methods for drastically improving the spot weldability of the vibration-damping composite sheet steel up to the same degree as that of conventional sheet steel.

The authors have been making research on developing vibration-damping composite sheet steel suited to direct spot-welding by the same method as the conventional one, and achieved the objective by blending the viscoelastic resin, which causes vibration-damping property, with graphite. This report first describes fundamental tests for giving electric conductivity to the intermediate resin layer and then explains the basic properties of vibration-damping composite sheet steel "NONVIBRA" which has been developed on the basis of the results of the fundamental tests.

2 Fundamental Tests

This chapter describes the results of the fundamental tests conducted for giving spot-weldability to vibration-damping composite sheet steel.

2.1 Test Method

2.1.1 Preparation of vibration-damping sheet steel sample

In making vibration-damping sheet steel for testing purposes, 0.6-mm-thick SPCE (DDQ steel) was used for skin sheet steel, and polythylene was used for resin as shown in **Table 3**, taking into consideration film formability of the resin when it is blended with graphite. To give electric conductivity to the resin layer, graphite particles were crushed and sifted out to adjust their average diameters within the range of 50 to 300 μm. Graphite content was changed within the range of 10 to 50 wt% of polyethylene.

Polyethylene pellets and graphite particles, which had been prepared in the above-mentioned way, were uniformly mixed and dispersed between two sheets of tefron as shown in **Fig. 2**, and hot-melted by a hot press machine available at the laboratory. The graphite-bearing polyethylene film thus made was sandwiched by two SPCE steel sheets and again hot-pressed to make a vibration-damping composite sheet steel.

Table 3 Materials used for the test

Material	Characteristics
Steel sheets	SPCE grade Thickness: 0.6 mm *TS* 32 kgf/mm², *YS* 19 kgf/mm², *El* 47 %
Graphite particles	Fine pieces smashed from carbon electrodes Diameter: 50 to 300 μm Content: 10 to 50 wt%
Resin	Polyethylene (PE) pellet with adhesiveness

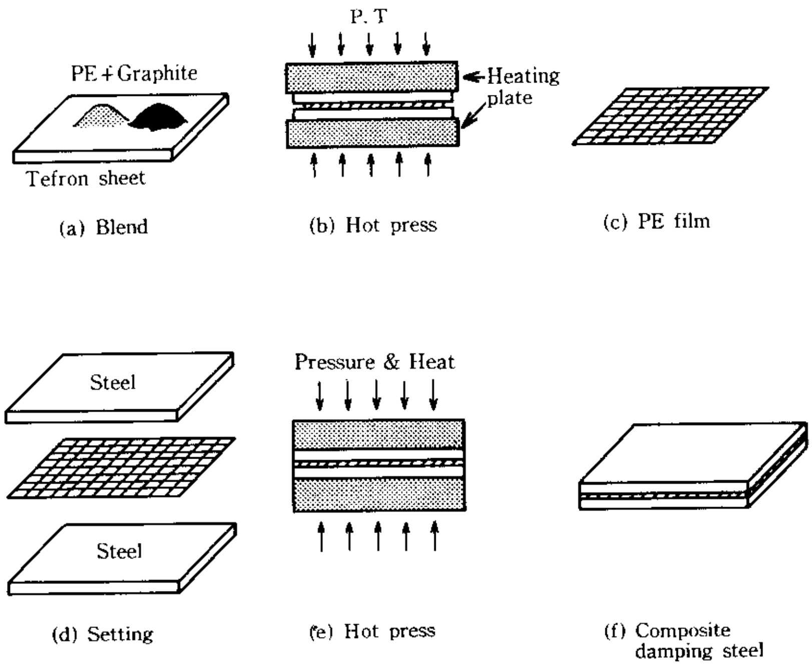


Fig. 2 Procedure of sample preparation

2.1.2 Test items

Table 4 shows the test items and the test conditions; **Figs. 3, 4,** and **5** show the loss factor, tensile strength of spot-welded joints, and shape and dimensions of the test piece for measuring adhesive strength between skin sheet steel and resin, respectively. The loss factor (Q^{-1}) which indicates vibration-damping performance was obtained by the mechanical impedance method[5] within the temperature range of 20 to 120°C. The test piece was placed horizontally and cramped at the center in the lengthwise direction. It was oscillated and its acceleration was measured at the same time (Fig. 3).

Table 4 Evaluation tests for composite damping sheet steels

Test item	Test condition	Measurement and evaluation
Damping property	20～120°C Mechanical impedance method	Loss factor (Q^{-1})
Spot weldability	Tip: CF type, 6.0 mm dia. Electrode force: 200-1 000 kgf Welding current: 6-12 kA	Nugget formation *TSS, CTS* Fracture mode
Adhesivity	−20～100°C INSTRON type	Lap shear strength

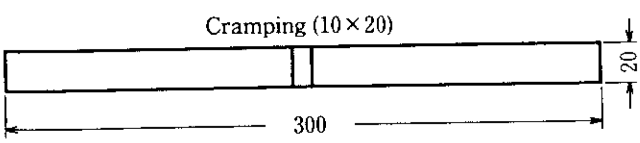
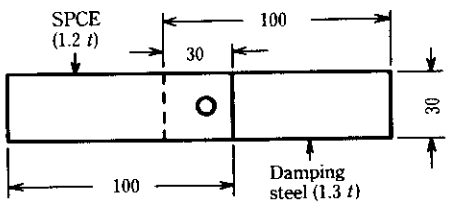
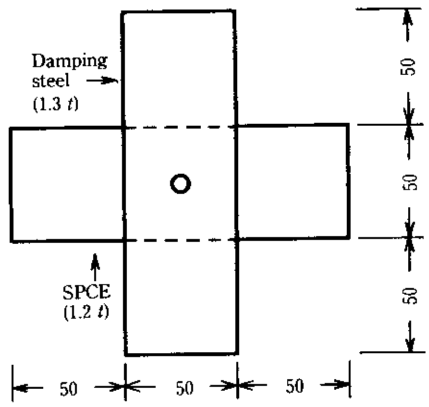


Fig. 3 Size of a test-piece for damping test



(a) Tensile shear strength



(b) Cross tension strength

Fig. 4 Configuration of spot welded joints used for tensile test (mm)

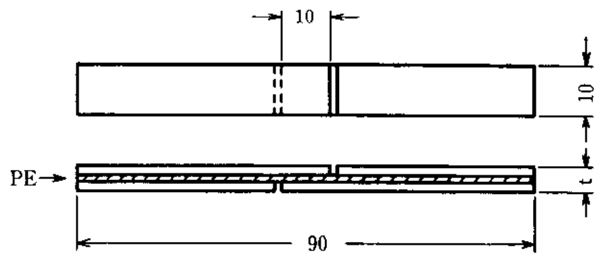


Fig. 5 Configuration of a test-piece for adhesivity test (mm)

To evaluate spot weldability, a vibration-damping steel sheet of about 1.3 mm in thickness was spot-welded to a 1.2-mm-thick SPCE steel sheet (DDQ steel sheet), as shown in Fig. 4, using a direct spot-welding machine (capacity: 600 kVA) manufactured by Man'yo Industry Co., Ltd. The tensile shear test and cross tension test were conducted in conformity with JIS Z 3136 and Z 3137, respectively. Evaluation items consisted of nugget formation, joint strength and the failure mode.

Adhesive strength between skin sheet steel and resin was measured on the basis of JIS K 6850. Figure 5 shows the shape of the test piece. Each vibration-damping steel sheet is given a notch by a precise cutting machine. Shear strength was measured and expressed in strength per unit area. The test-piece temperature was changed within the range of −20 to +100°C.

2.2 Test Results

What should considered in adding graphite to resin are the average particle diameter (D_g), quantity of addition, and the size distribution of graphite. **Figure 6** shows the spot-weldability of vibration-damping steel sheets which were made by adjusting D_g to 200, 150 and 100 μm and by changing film thickness (t_r) within the range of 50 to 500 μm, while maintaining the quantities of graphite added to polyethylene at 30, 30, and 20 wt% respectively. The figure indicates in all cases that as film thickness t_r becomes greater than average particle diameter D_g of graphite, the success rate of spot welding drops. This reveals that the success rate of spot welding is affected not only by the magnitude of D_g, but also by t_r, which has an important meaning, and that if the D_g/t_r ratio is 0.8 to 1.0 or above, the success ratio will be 100%. Figure 6 shows the case in which D_g is greater than t_r. Since D_g indicates the value before film formation and t_r shows the value after making the vibration-damping steel, it is considered that graphite particles have been crushed at the stage of making the vibration-damping steel.

Figure 7 shows the effect on spot weldability of the amount of addition and average particle diameter of graphite and electrode force, when film thickness is maintained at about 200 μm. The spot-weldable range

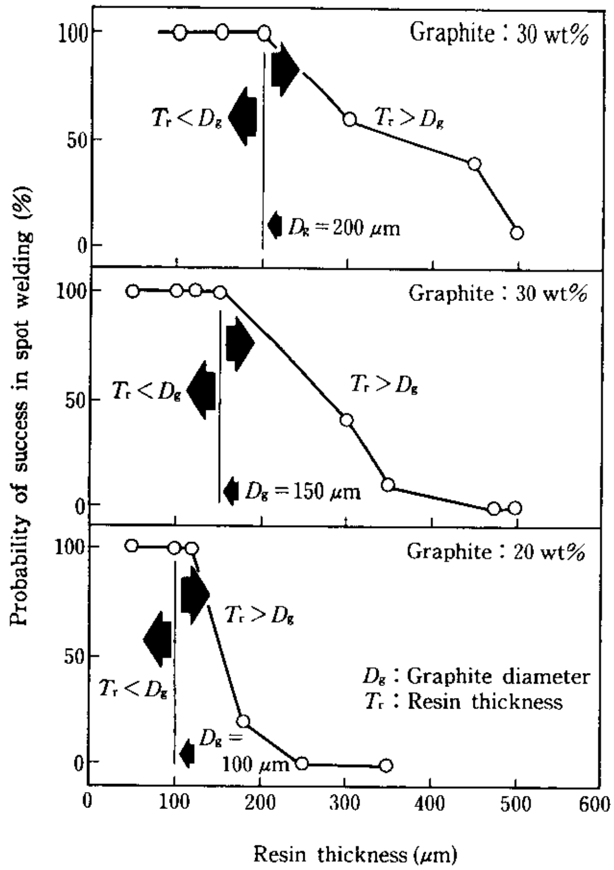


Fig. 6 Effect of resin thickness on spot weldability (Electrode force: 200kgf)

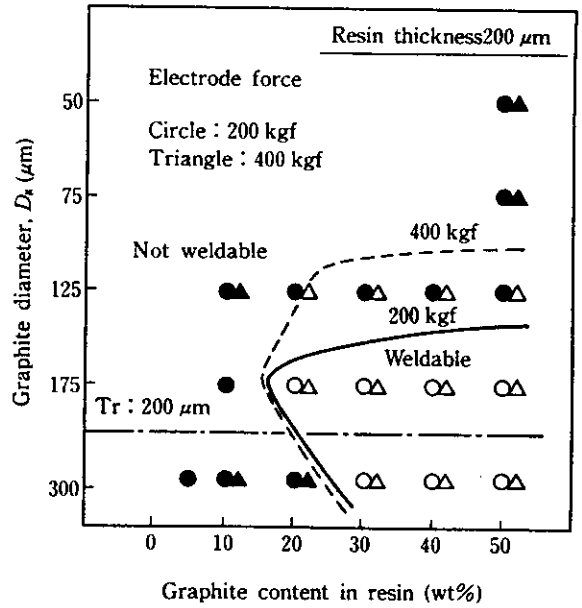
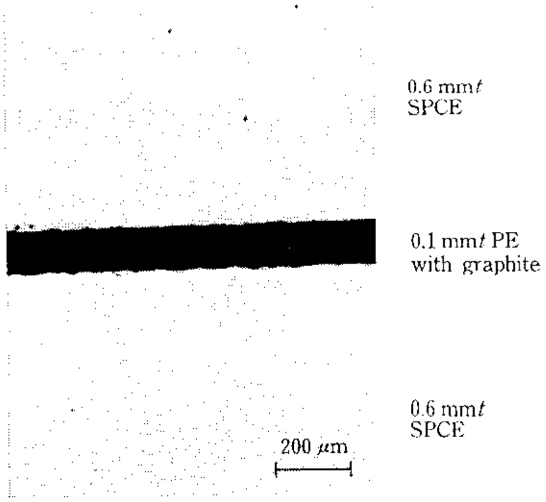


Fig. 7 Effect of content and average particle diameter of graphite on spot weldability (Electrode: CF 6.0 mmϕ Welding current: 10 kA × 12 cycles)

(the range of conditions under which the success rate of spot weldability becomes 100%) becomes the maximum, when the average particle diameter becomes



(a) Base metal (before etching)

(b) Spot welded joint (after nital etching)

Photo 1 Structure of spot-welded composite-steel joint (Electrode: CF, dia., 6.0 mm, 270 kgf; Welding current: 9.8 kA × 12 cycles)

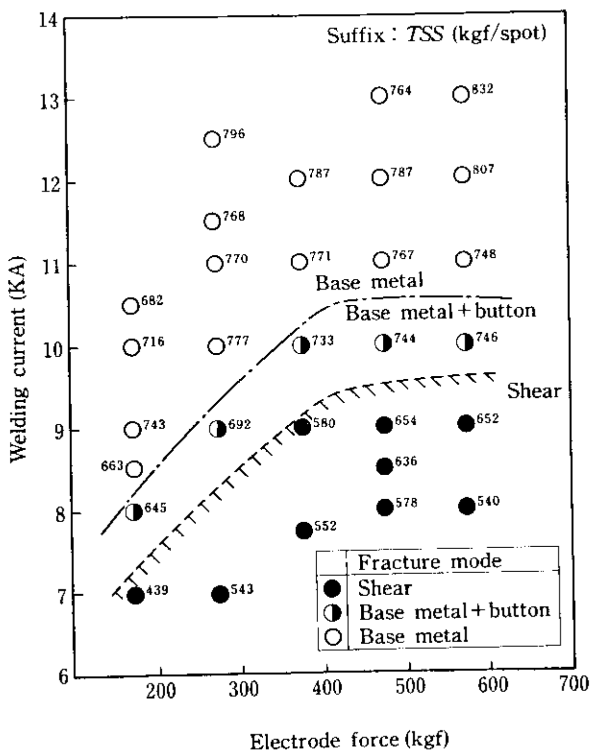


Fig. 8 Effect of welding current and electrode froce on tensile shear strength when a composite damping sheet (0.6:0.1:0.6 mm$t$) was spot-welded with a SPCE grade steel sheet (1.2 mm$t$)

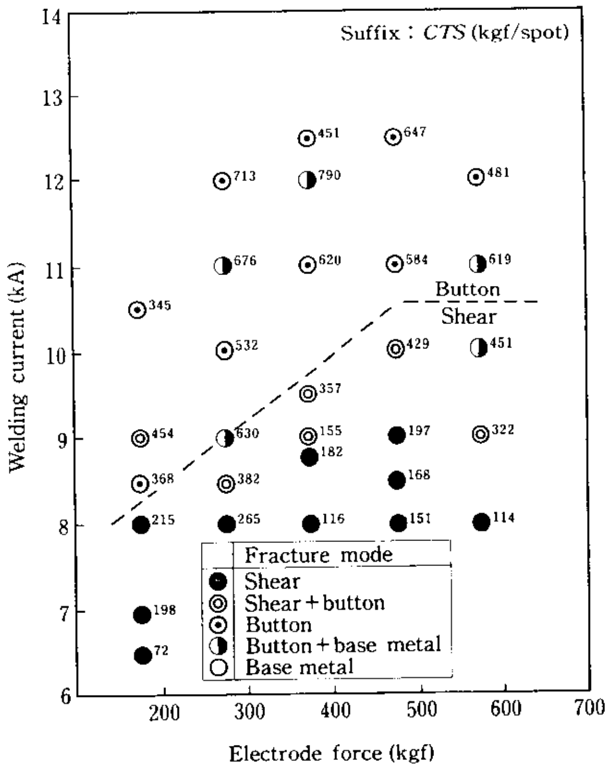


Fig 9 Effect of welding current and electrode force on cross tension strength when a composite damping sheet (0.6:0.1:0.6 mm$t$) was spot-welded with a SPCE grade steel sheet (1.2 mm$t$)

175 μm which is slightly smaller than the film thickness of 200 μm, and even at a graphite addition of 20 wt%, excellent spot weldability is obtained. When electrode force is raised from 200 kgf to 400 kgf, the spot-weldable area expands towards the smaller particle diameter of graphite, and excellent spot weldability can be obtained even at D_g of 125 μm.

Photo 1 shows the micrograph of cross section of the weld of a vibration-damping steel sheet with t_r of 0.1 mm, a graphite addition of 20 wt%, and D_g of 80 μm. A nugget is formed over three steel sheets, that is, two steel sheets of 0.6 mm in thickness which form the vibration-damping composite steel sheet and a 1.2-mm-thick SPCE steel sheet. The photo of base metal of the vibration-damping steel sheet indicates that some graphite particles are contained in the resin film.

Figures 8 and 9 show the effects of spot-welding conditions on tensile shear strength (*TSS*) and cross tension strength (*CTS*), respectively. In these figures, the above-mentioned vibration-damping composite steel sheets of 0.6/0.1/0.6 mm in thickness and 1.2 mm-thick SPCE sheets have been spot-welded. Numerals indicate the tensile shear strength or cross tension strength in units of kgf/spot. Figure 8 shows that *TSS* comparable to that which can be obtained in spot welding of two SPCE sheets within a wide welding condition range can be obtained. The fracture mode of the weld becomes a shear mode when the welding current is lower, and becomes base metal fracture when the welding current is higher. This is the same as the case of spot welding of two SPCE sheets. On the other hand, Fig. 9 that the

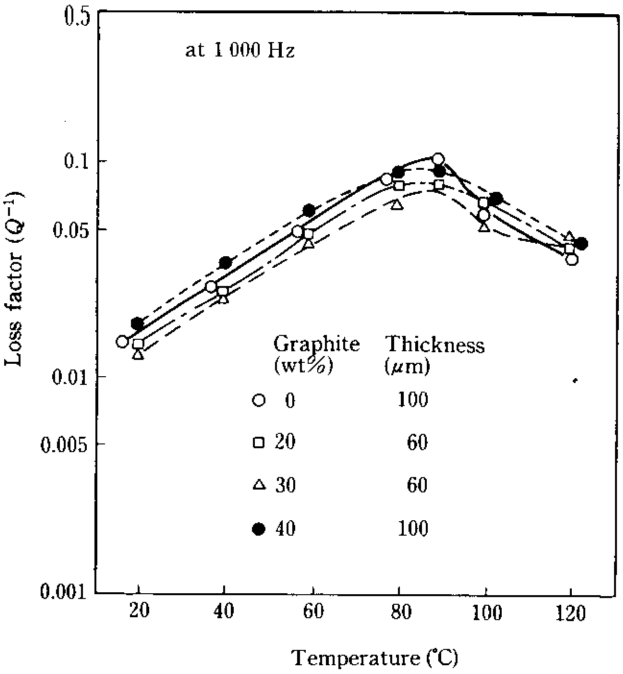


Fig. 10 Effect of graphite addition on temperature dependency of loss factor

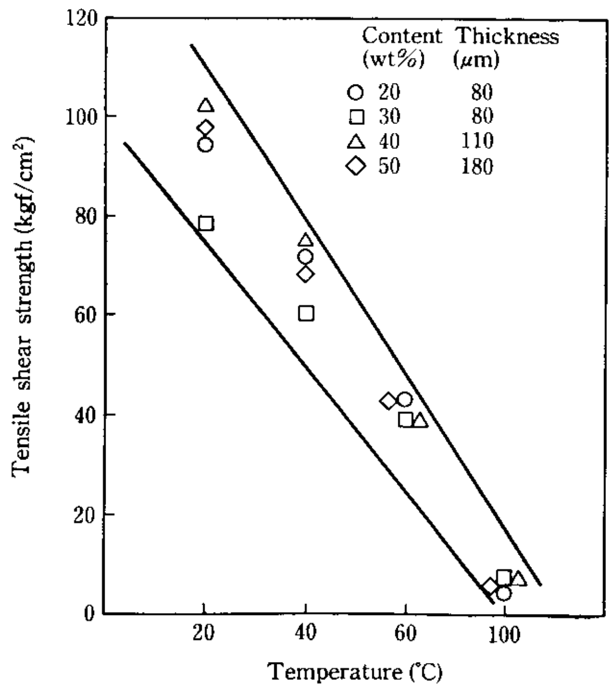


Fig. 11 Effect of graphite addition on temperature dependency of adhesive strength

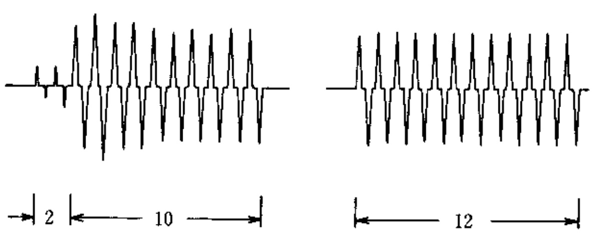
value of *CTS* is generally lower than that of *TSS* and shows wide dispersion. The reason for this is that it is difficult for uniform force to be applied to two skin steel sheets which compose the vibration-damping steel, and thus the stress condition tends to become the same as that which occurs when a 1.2-mm-thick and a 0.6-mm-thick SPCE sheets are spot-welded. Referring to the failure mode of the weld, there is no base metal fracture, but only shear fracture or button-shape fracture exists.

There is almost no effect of graphite addition on the temperature dependency of the loss factor (**Fig. 10**), and shear strength does not drop noticeably, either (**Fig. 11**). From the above, it has been found that graphite addition to resin is an effective method for giving spot weldability to the vibration-damping composite sheet steel, and scarecely has adverse effects on vibration-damping property and adhesive strength.

2.3 Welding Mechanism

The authors have investigated the phenomenon which occurs when graphite-added composite vibration-damping steel sheets are spot-welded, and have examined the mechanism through which spot weldability is imparted by graphite addition.

Figure 12 shows a comparison in secondary current behavior between spot welding of two vibration-damping composite steel sheets and that of two conventional steel sheets. In the latter case, the secondary current flows according to the set value starting from the initial half cycle, whereas in the former case, the secondary current of only about one-third of the set value flows for the initial two cycles. Such a current behavior in spot welding of vibration-damping composite steel sheets resembles preliminary current conduction[6] for preheating the resin by installing a bypass in the case of vibration-damping sheet steels manufactured by other steel mills, and thus it is considered that graphite in the film



(a) On the spot welding of a composite damping sheet (0.6 : 0.1 : 0.6 mm*t*) with a SPCE grade steel sheet (1.2 mm*t*)

(b) On the spot welding of two 1.2 mm*t* sheets of SPCE grade steel

Fig. 12 Comparison of secondary welding current (Electrode: CF, 6.0 mm dia., 300 kgf; Welding current: 10 kA × 12 cycles)

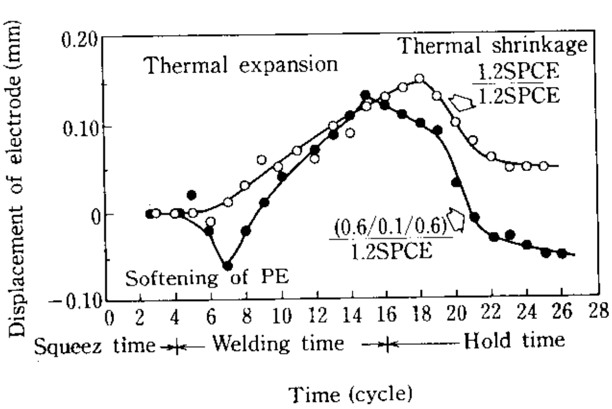


Fig. 13 Comparison of electrode displacement during spot welding
(Electrode: CF, 6.0 mm dia., 300 kgf
Welding current: 10 kA)

becomes a current conduction circuit at the initial stage of current conduction, and heats and softens the resin, thereby causing the two skin steel sheets which compose the vibration-damping sheet steel to come into direct contact. In other words, the role played by the spot-weldable vibration-damping sheet steel developed by Kawasaki Steel consists in eliminating the process of bypass installing which is a part of welding operation. For this reason, the use of Kawasaki Steel's vibration-damping composite sheet steel will make it possible to obtain a sound and stable weld quality without variation in weld quality depending on the weld pitch as in the bypass method.

Figure 13 shows the results of the monitored movement of the electrode tip during spot welding. For the vibration-damping composite sheet steel, the tip descends at three cycles in the initial stage of current conduction (indicating that the film has become thinner by 0.06 mm), and softening of the resin is clearly observed.

From the above test results, current conduction circuit formation by graphite is schematically expressed in **Table 5**. Assuming that film thickness and graphite content remain constant, the distribution of graphite in the film will be divided into three kinds, i.e., "fine grain and high density," coarse grain and low density", and their "intermediate state."

In the case of the "fine grain and high density," graphite particles are uniformly disperesed in the film, and even if the film becomes thinner due to electrode force, mutual contact between graphite particles is difficult to occur, thereby making spot welding partically impossible. Even in this case, however, if a method is taken whereby to preheat resin by installing the bypass circuit, welding is made much easier with more stable weld quality than in the case of no graphite addition.

As for the "coarse grain and low density," on the other hand, the ease in current conduction makes spot welding possible, but sometimes the current does not take the shortest distance between electrodes, but makes a detour, thereby making weld quality unstable. As for the "intermediate state," a current path of "electrode–skin steel–graphite–skin steel–electrode" is formed by electrode force, and stable weld quality can be obtained.

To verify the existence condition of graphite shown in Table 5, calculations shown below have been made. Let's assume that the graphite particle has a spherical shape (with a radius of r) and consider that n pcs of such graphite particles are arranged in a lattice form at a pitch of d within a square shape of the film (with a film

Table 5 Mechanism of improvement in spot weldability

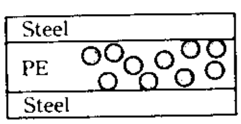
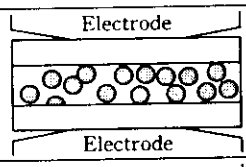
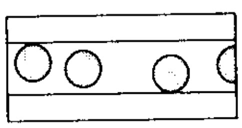
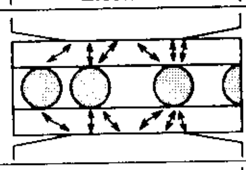
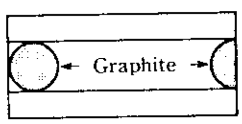
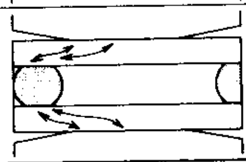
Graphite particle			Spot welding	Spot weldability
Diameter	Density	Distribution in PE		
Fine	High			Poor (impossible)
Proper	Middle			Good (stable)
Coarse	Low			Good (unstable)

Table 6 Mechanical properties of composite damping steels

	Steel	Direction	*YS* (kgf/mm²)	*ST* (kgf/mm²)	*El* (%)	*Y.El* (%)	$\bar{r}$	*LDR*
Deep drawing steel	KTU-X (0.8 mm *t*)	L	14	30	51	0	2.06	2.21
		T	15	30	53	0		
		D	15	31	49	0		
Damping steel for use at room temperature	KTD-C(R) (0.8/0.1/0.8 mm *t*)	L	14	29	51	0	2.02	2.21
		T	14	29	53	0		
		D	15	31	49	0		
Damping steel for use at middle temperature	KTD-C(M) (0.8/0.1/0.8 mm *t*)	L	14	30	51	0	2.02	2.21
		T	14	30	51	0		
		D	15	30	48	0		

Tensile test: JIS No.5, G.L.=50 mm
LDR test : Punch dia. 33 mm, BHF 500 kgf, Lubricant G 790

thickness of t) having a side l. When the density values of the resin and graphite are denoted by ρ_r and ρ_g, respectively, and the weight ratio of graphite content to resin is denoted by R, the following two equations are obtained:

$$\frac{(4/3)\pi r^3 \times n^2 \times \rho_g}{\{tl^2 - (4/3)\pi r^3 \times n^2\}\rho_r} = R \quad \cdots\cdots\cdots\cdots(1)$$

$$l = d \times n \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(2)$$

Assuming that the particle diameter of graphite is equal to film thickness to make the calculations simpler, namely, assuming that $t = 2r$, graphite interval d can be expressed by

$$d = \left(\frac{\pi \rho_g}{6R} + \frac{\pi \rho_r}{6}\right)^{1/2} t \quad \cdots\cdots\cdots\cdots\cdots\cdots(3)$$

If it is assumed that $t = 0.1$ mm and $R = 0.20$, we obtain $\rho_g = 2.3$[7] and $\rho_r = 0.9$[8], thereby obtaining $d = 0.25$ mm.

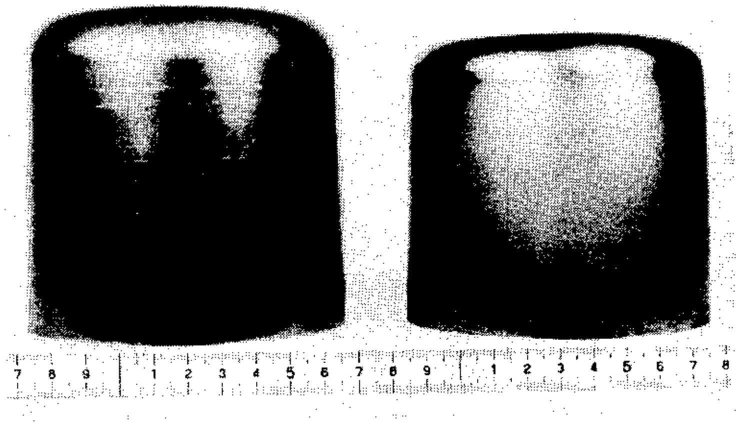
The vibration-damping steel sheet shown in Photo 1(a) gives the following values: $t = 0.1$ mm, $R = 0.20$, and $2r = 0.8t$; thus $d = 0.20$ mm is obtained by calculation, which means that five graphite particles lie in the film of 1.0 mm in length. Photo 1(a) indicates nearly the same condition. The edge diameter of the electrode tip is 6.0 mm, which means that about 700 graphite particles exist in the film which lies in the area pressed by the tip, thereby guaranteeing the uniformity of current conduction.

3 Characteristics of Spot-weldable Vibration-damping Composite Sheet Steel "NONVIBRA"

On the basis of the above-mentioned fundamental tests for development, we have developed vibration-damping composite sheet steel "NONVIBRA" having a high loss factor and capable of spot welding. For the skin sheet steel, non-aging EDDQ cold-rolled sheet steel "KTUX" has been used to eliminate trouble arising from aging due to the heat effect during the making of the vibration-damping sheet steel (designation: KTD-C). For the skin sheet steel, hot rolled sheet steel and surface-coated sheet steel can also be used.

Table 6 shows mechanical properties of vibration-damping sheet steel for room temperature use, **KTD-C(R)**, and vibration-damping sheet steel for middle temperature use, **KTD-C(M)** (0.8/0.1/0.8 mm*t* for both), and skin sheet steel, KTU-X (0.8 mm*t*). Tensile properties of the vibration-damping sheet steel and skin sheet steel are almost the same and their $\bar{r}$ values and limiting drawing ratios (*LDR*) which can be used as rough guides to drawing formability are also equal. **Photo 2** shows cups obtained by deep-drawing the vibration-damping steel sheet for room temperature, KTD-C(R) (0.8/0.08/0.8 mm*t*), and SPCE sheet (1.79 mm*t*) using the Erichsen tester. The punch diameter is 100 mm, punch-nose diameter 12 mm, and the radius of curvature of the die lip 4 mm. Blank holder forces are 5 and 3 t, respectively. Both cups were drawn at the state near the limiting drawing ratio (at 2.20 and 2.05, respectively), and edge-cut by about 5 mm. Since KTD-C (NONVIBRA) has better drawability than that of SPCE, it can be used for making oil pans which must undergo particularly severe drawing out of automobile parts. As shown in **Photo 3**, the flange of the deep drawn cup is spot-welded, but if it is seam-welded, the cup can be used as a cover for the air compressor.

Figure 14 shows the welding current behaviors of vibration-damping sheet steel (KTD-C) for room temperature and middle temperature during spot-welding.



(a) NONVIBRA KTD-C (b) SPCE

Photo 2 Cups drawn by Erichsen testing machine

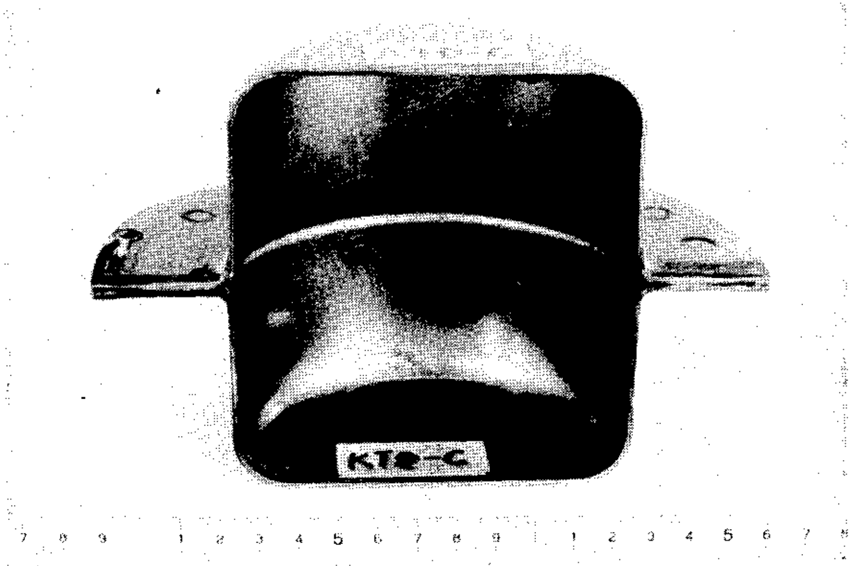


Photo 3 A spot welded model component using NON-VIBRA KTD-C

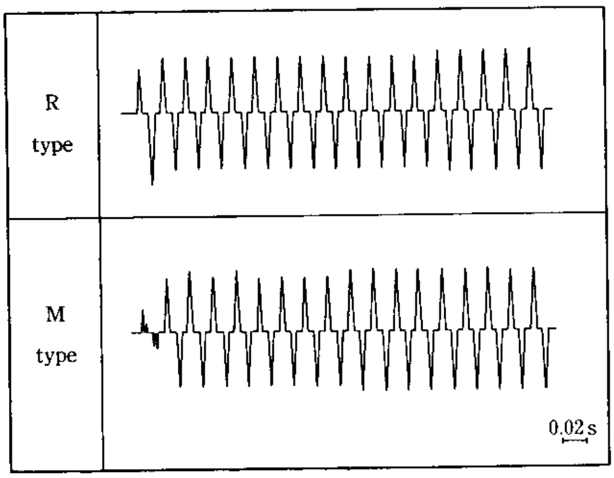


Fig. 14 Welding current of NONVIBRA KTD-C for room temperature use (R) and middle high temperature use (M)
(Electrode: CF, 6.0 mm dia., 390 kgf
Welding current: 11 kA × 18 cycles)

In KTD-C for room temperature, a welding current nearly equal to the set value flows from the start. In KTD-C for middle temperature, a weak welding current flows for the initial few cycles (playing the role of pre-heating the resin), and then the secondary current flows according to the set value. Seam welding can also be easily applied in exactly the same way as before as in the case of direct spot welding.

Temperature dependency of the loss factor is shown in **Fig. 15**, and all KTD-C sheets for room, middle and high temperatures have the maximum loss factor value of about 0.5, indicating the less temperature dependency of all these sheets. In using them, right type of sheet should be properly used for right working temperatures, as they can be accommodated to applications within the range of from room temperature to 120°C. At present KTD-C and KTD-H are enjoying favorable acceptance by users following the result of user tests, and are

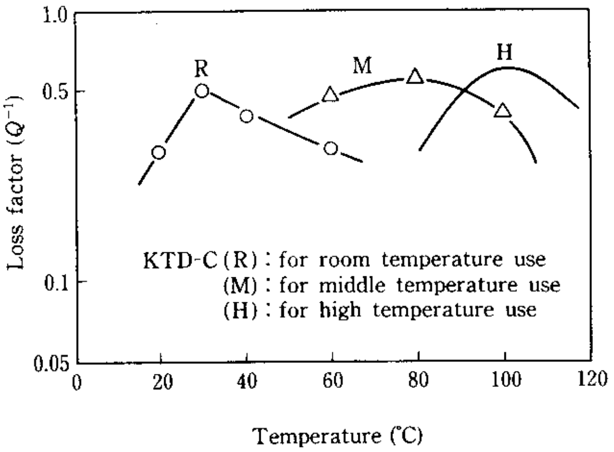


Fig. 15 Temperature dependency of Q^{-1} in three types of NONVIBRA KTD-C

expected to contribute to preventing vibration, noise generation, and fatigue fracture.

4 Concluding Remarks

Vibration-damping composite sheet steel (NONVIBRA, KTD-C), which is suited to direct spot welding in the conventional way by adding graphite to a viscoelastic resin, has been developed, and the following points been found in the process of its development:

(1) The role played by graphite during spot welding is to provide a current path at the beginning of spot welding and replace a bypass installation or an auxiliary electrode.

(2) The amount of graphite addition can sufficiently be the smallest, when the graphite particle diameter is slightly smaller than resin thickness. Then the film thickness and particle diameter become exactly equal during the application of electrode force, thereby forming a current path.

(3) When a spot-welded joint between KTD-C and SPCE is compared in strength with that between two SPCE's, the former is slightly inferior to the latter in cross tension strength, but nearly equal in tensile shear strength.

(4) There is no adverse effect exercised by graphite addition on the loss factor and adhesive strength.

(5) The KTD-C sheet made of EDDQ steel sheets has higher drawability than that of the SPCE sheet having the same thickness.

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