Investigation on Welding Arc Sound (Report 4)†
– Vibration Analysis of Base Metal during Welding –

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Abstract

Vibration of base metal at CO_2 arc welding was measured in order to clarify its characteristics as well as its correlation with the behavior of molten pool and the welding arc sound.

Vibration, especially that in low frequency region can be detected fairly accurately with a piezoelectric accelerometer of the sensibility of 100 mV/G class, and the vibration has a good competence as the information signal to exhibit the behavior of molten pool.

KEY WORDS: (Acoustics) (Arc Welding) (Process Panameter) (Environment)

1. Introduction

The vibration of base metal at arc welding hereinafter called "welding vibration" is said to affect the formation of bead wave[1–3], and is expected to be significant to study the fluid behavior and solidificant process of molten pool. However, few systematic studies have been done on welding vibration and its characteristics have been known little.

In this paper, welding vibration was detected with a piezoelectric accelerometer of high sensibility of 100 mV/G class in order to clarify its chracteristics as well as its correlation with the behavior of molten pool and the welding arc sound.

2. Experimental Apparatus and Procedures

Bead-on-plate welding was applied to SM41B steel plate (size: 50 x 12-500 mm) by use of CO_2 arc welding method in an anechoic room. Principal welding conditions are given in **Table 1**. Welding vibration was detected with an piezoelectric accelerometer (BBN, Model-507, sensibility: 97.4 mV/G, response frequency: 2 ~ 12,000 Hz, horizontal sensibility: 5%) installed on a welding bench (a disk of the effective radius of 350 mm made of SS41 steel of which periphery was fixed) as shown in **Fig. 1**. According to a hammering test, the frequency of vibration of the normal mode f_0 was 253 Hz when material to be welded was fixed on the welding bench with a fixture. The form of vibration was relatively simple. The welding

Table 1 Welding conditions.

Welding Current (A)	200~400
Arc Voltage (V)	Variable
Welding Speed (cm/min)	20 (~100)
Gas Flow Rate (l/min)	20
Wire Extension (mm)	20
Wire Diameter (mm)	1.6 (1.2)
Torch Angle (°)	90
Polarity	D.C.R.P

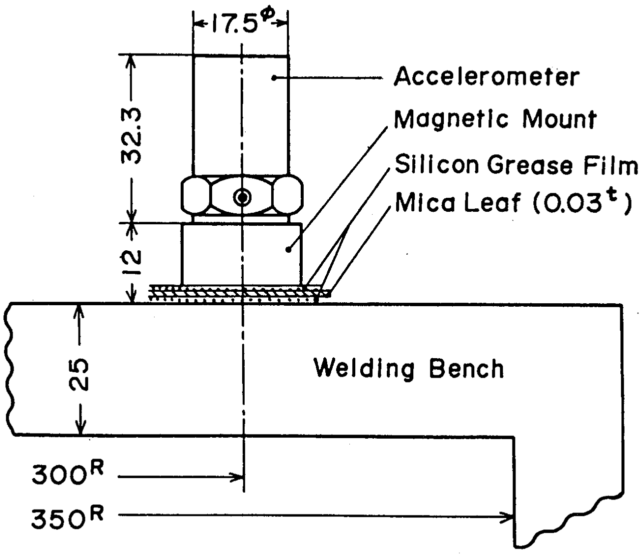

Fig. 1 Schematic arrangement of apparatus for measuring welding vibration.

† Received on March 31, 1981

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Suita, Osaka, Japan

bench was completely separate from the part of welding torch in order to cut off the noise which is produced when the part of welding torch is moved.

The behavior of molten pool suggests that welding vibration is one of multiple freedom. However, vibration in only one vertical direction is considered here. The analytical method of the welding arc sound[4-6] up to the region of 3000 Hz was adopted to analyze the frequency spectrum of vibration because the frequency which affected the hard ware was up to about 2000 Hz.

3. Exprimental Results and Discussion

3.1 The waveform of welding vibration (acceleration)

Examples of waveform of welding vibration are shown comparing with the waveform of welding current in **Fig. 2.** **-(a)** and **-(b)** are for the condition of Dip transfer arc, **-(c)** is for buried arc of Globular transfer arc, and **-(d)** is Globular transfer arc relatively longer arc length. The

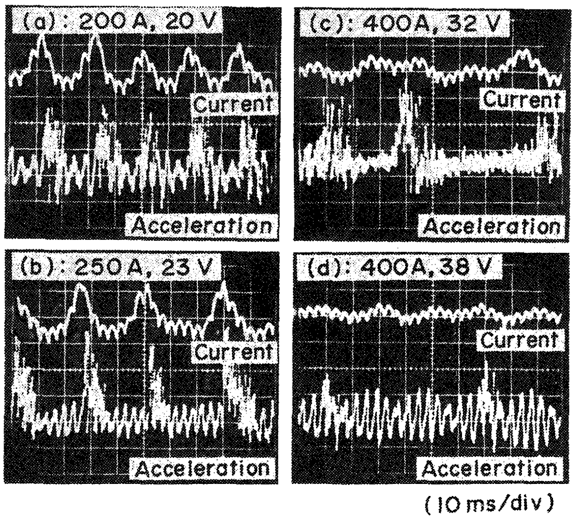

Fig. 2 Examples of acceleration waveforms of welding vibration and welding current waveforms.

waveform of welding vibration varies characteristically to considerable extent depending on the type of particle transfer and the arc length.

The sine wave of each oscillogram is a composite waveform consisting of the ripple component (f_R = 300 Hz) in the output current and the characteristic vibration component (f_0 = 253 Hz) of material to be welded including the welding bench as clearly shown by the analysis of frequency described later. The amplitude of this waveform tends to increase as the current and the arc length increase similarly as the waveform of the sound pressure of welding arc[4].

As for the impulse wave form, waves of similar amplitude and duration appear cyclically synchronously with the reignition of arc in -(a) and -(b). On the other hand, waves of a little longer duration appear a little irregularly in -(c), and ones of shorter duration appear in -(d). However, it is found also in -(c) and -(d) by observing the oscillogram of long time that impulse waveforms appear relatively cyclically and the period seems to correspond to the period of the separation of droplets.

Observing the impulse waveforms of -(a), -(b) and -(c) in more detail, it is found that they don't show simple attenuation process and most of them seem to be produced by multiple impulse force.

The impulse waveform varies depending on welding speed. The duration time tends to become shorter as welding speed increases, even for buried arc.

Basing on observations described above, the mechanism of generation of impulse waves can be explained as follows; impulse waves are generated by the vibration of molten pool given by impulse force due to explosive fuse action at the reignition of arc in the case of Dip trasfer arc condition, or at the separation of droplets in the case of Globular transfer arc condition, and then by the action of the force of arc at the reignition or just after the separation of droplets on molten pool. It is evident from the observation of the state of the generation of spatter and the waveform sound pressure[4] that the fuse action at the reignition of arc and the separation of droplets is accompanied by the generation of considerable pressure.

In the case of buried arc where the shape of molten pool is complicated, the force of arc is apt to act locally and directly, which is clearly suggested by the fact that arc is generated preferentially where geometrically the shortest distance is obtained. In this way the difference of impulse waveforms can be explained well. (Figure 5 shall be referred to concerning the influence of the arc length on the behavior of arc, and Figure 9 in the previous report[4] shall be referred to concerning the influence of the speed of welding.)

3.2 Correlation between welding vibration and the welding arc sound

The sound intensity of welding arc depends on the method of welding and welding conditions. The sound pressure level, SPL, (= $20 \log_{10} P_e/P_{eo}$, $P_{eo} = 2 \times 10^{-5}$ P_a) sometimes exceeds 100 dB[4]. SPL = 100 dB corresponds to 2 P_a of sound pressure, and 10^{-2} W/m^2 of intensity. Concequently it is expected that the welding arc sound acts as one of the causes of welding vibration, and that there exists correlation between them.

The magnitude of the vibration of welding bench was measured when white noise was produced from a speaker

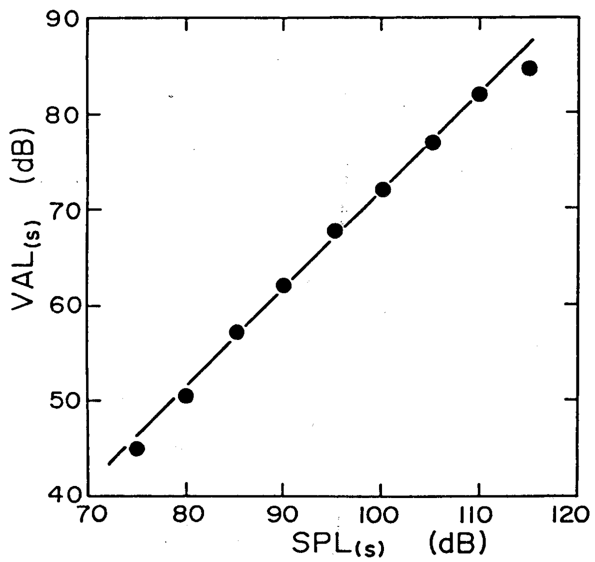

Fig. 3 Correlation between sound pressure level, $SPL_{(S)}$, and vibration acceleration level, $VAL_{(S)}$, at white noise.

placed 400 mm above it. **Figure 3** shows the correlation between the sound pressure level, $SPL_{(S)}$, and the vibration acceleration level, $VAL_{(S)}$. $VAL_{(S)}$ is proportional to $SPL_{(S)}$, which is approved theoretically, too. $VAL_{(S)}$ is defined here as

$$VAL_{(S)} = 20 \log_{10} \alpha_e / \alpha_{eo} \qquad \text{dB}$$

where α_e is an arbitrary vibration acceleration and α_{eo} is a standard vibration acceleration. $\alpha_{eo} = 10^{-5}$ m/s² has been adopted taking the draft of ISO/TC43 into consideration.

The correlation between the sound pressure level, SPL, and the vibration acceleration level, VAL, was studied for practical CO_2 arc welding in which the welding current was kept constant at 200 A and 400 A, and the arc voltage was varied. The result is shown in **Fig. 4**. VAL

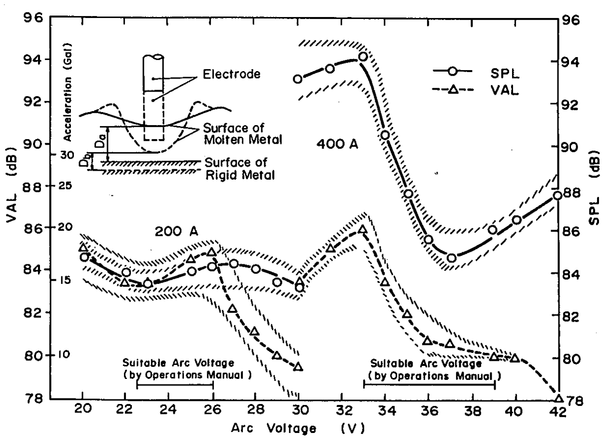

Fig. 4 Variations of vibration acceleration level, VAL, with sound pressure level, SPL, at various welding conditions.

changes in a similar way as SPL within a relatively wide range including the appropriate arc voltage range (according to the handling manual of the welder). But in the range of excessive arc voltage VAL tends to decrease in spite of the increase in SPL. Further another characteristic is that VAL varies depending on the condition of current and voltage even for an identical SPL. Thus they don't show such a simple proportional correlation as Fig. 3.

Seeing the facts described above in connection with welding arc phenomena, one of the causes of the tendency of decrease in VAL for higher arc voltage (longer arc length) is assumed that the thickness of molten metal layer directly below the arc is greater than that for shorter arc and the attenuation loss in the propagation process of vibration becomes greater. This assumption is supported by the frequency analysis of the waveform of vibration acceleration that the spectrum component becomes smaller in the higher frequency region for longer arc length. The drawing attached to Fig. 4 shows shematically the thickness of molten metal layer for the conditions of long arc length (D_a) and short arc length (D_b). Vibration acceleration level in Fig. 4 (practical welding) is greater than that for the identical sound pressure level in Fig. 3, which suggests that welding vibration is affected not only by welding arc sound but also by other vibration sources such as the vertical motion of molten metal.

3.3 Photographic observation of molten pool

Examples of high-speed motion photographs are shown in **Fig. 5 - (a), (b)**. (photographs were taken in the direction approximately parallel of perpendicular to welding line). It is observed from -(a) for Globular transfer arc and buried arc that the whole molten metal undulates cyclically up and down keeping fine surface wave of ripples and a deeply depressed form directly below the arc. (Photos 1 to 32 correspond to approximately one cycle. The apparent difference of wave height between No.14 and No.24 is about 4 mm). One cycle of this undulation is apparently formed by the gradual expansion of the belly of the displacement (No.14) toward the periphery formed by the combination of wave with round head growing relatively gradually behind the wire and triangle wave being generated rapidly ahead the wire just after the separation of droplets (No.2, No.32, when molten pool becomes rough).

In the case of -(b) for Globular transfer arc and long arc length, molten metal is slightly depressed directly below arc and undulates monotonously and smoothly as a whole, though considerable generation of spatter is observed at the separation of droplets (No.31). This sort of behavior of molten metal is similar to the correlation be-

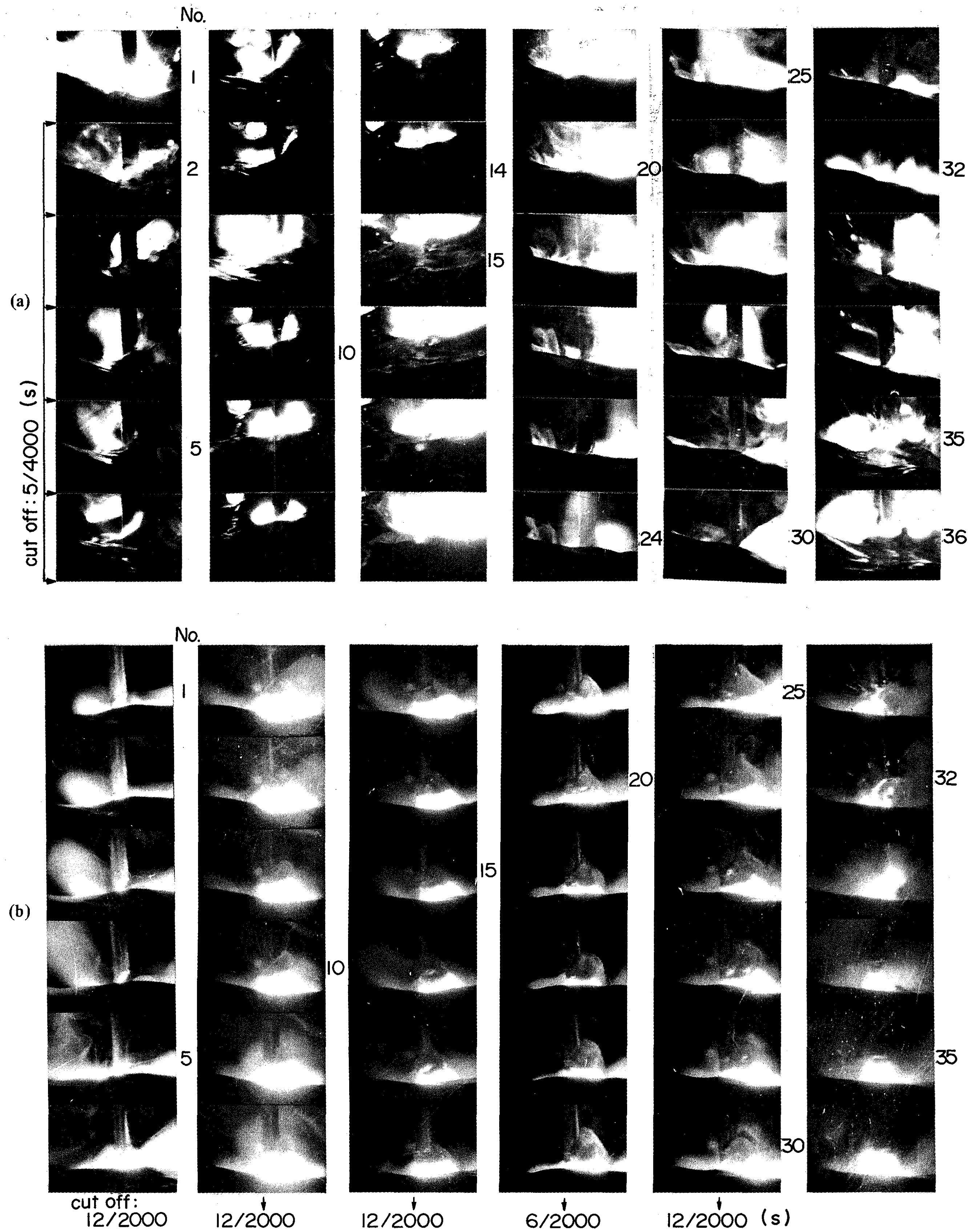

Fig. 5 High-speed motion photographs of molten metal.
-(a): 400A, 32V (4000 frames/s), -(b): 400A, 32V frames/s), -(b): 400A, 38V (2000 frames/s)

tween "wind wave" and "undulation" on the sea, and -(a) corresponds to the case in which they are both strong.

These observations support well the explanation described above about the waveform of welding vibration and are in good agreement with the fact shown in Fig. 4 that VAL decreases and width of its variation becomes small in the case of long arc length.

Images on films for Fig. 5-(a) and -(b) were optically magnified and projected on frosted glass and the vertical motion of molten metal was transformed to electricity with a photoelectric element (NEC, P032H) mounted on the frosted glass through a slit. The examples are shown in **Fig. 6**. (The output signal has been smoothed.) The cycle of the undulation is about 50 ms for both 400A-32V and 400A-38V. This cycle is in good agreement with the result of the analysis of the waveform of welding vibration in the region of low frequency (see Fig. 11) and corresponds approximately to the frequency of the separation of droplets f_G $(=3V_W/(4\pi a^3))$ calculated from the quantity of wire feeding per a unit time V_W and the assumption of droplets to be spheres of radius a.

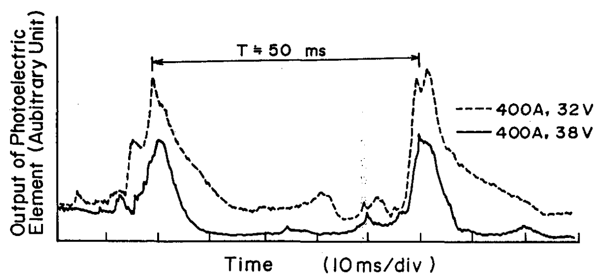

Fig. 6 Examples of output signal from photoelectric element.

3.4 Results of frequency analysis of welding vibration (high frequency region)

Results of the frequency analysis of the waveform of welding vibration for the cases of Dip transfer arc and Globular transfer arc are shown in **Fig. 7-(a)** and **Fig. 8-(a)**. The results of the analysis of the waveform of welding arc sound pressure are shown in **Fig. 7-(b)** and **Fig. 8-(b)** for reference.

Components corresponding to short-circuit frequency f_D (Fig. 7-(a)), the frequency of droplets separation f_G (Fig. 8-(a)), the ripple frequency of output current f_R and its higher harmonics mf_R, and the frequency of vibration of the normal mode of material to be welded including the welding bench f_o and its higher harmonics mf_o (m = 2,3, ...) are observed in the frequency spectrum of welding vibration.

The ratio of the most characteristic three spectrum components f_D (or f_G), f_R and f_o to the strength of the

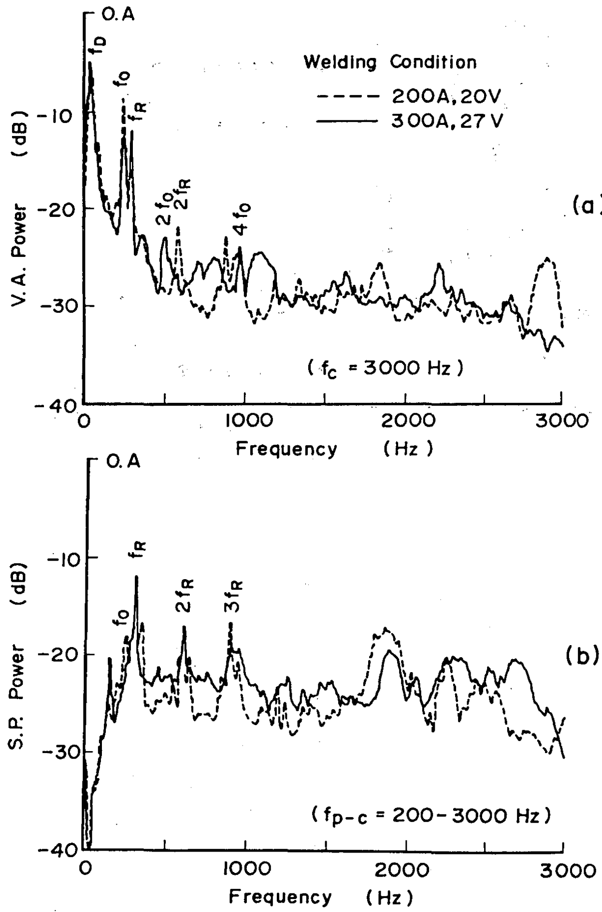

Fig. 7 Power spectrum of acceleration of welding vibration (a) and welding arc sound (b) on Dip transfer arc at high frequency region.

whole frequency component has been calculated as shown in **Fig. 9**. The ration of each component depends on the condition of welding. The highest ratio is occupied by f_D for Dip transfer arc and f_G for Globular transfer arc. Since these three components occupy 50% to 70%, they can be assumed to affect more or less the formation of bead wave. (But f_o component is not caused by the phenomenon of welding itself).

Garland et al.,[1] Kotecki et al.[2] and Nakane et al.[3] studied the mechanism of the formation of bead waveform in TIG arc welding and confirmed the existence of wave in bead wave corresponding to f_R. However the existence of wave corresponding to f_o has not been mentioned. In their experiments thin plates (thickness: 1.067 ~ 3.175 mm. their shape is not clear) were used which was probably the reason that f_o was too higher than f_R and no wave corresponding to f_o did not appear.

The results of the frequency analysis of welding arc sound were already reported[4-6], and they will not be described here in detail. There spectra corresponding to components of f_R, mf_R and f_o were observed and the spectrum profile was similar to welding vibration as a

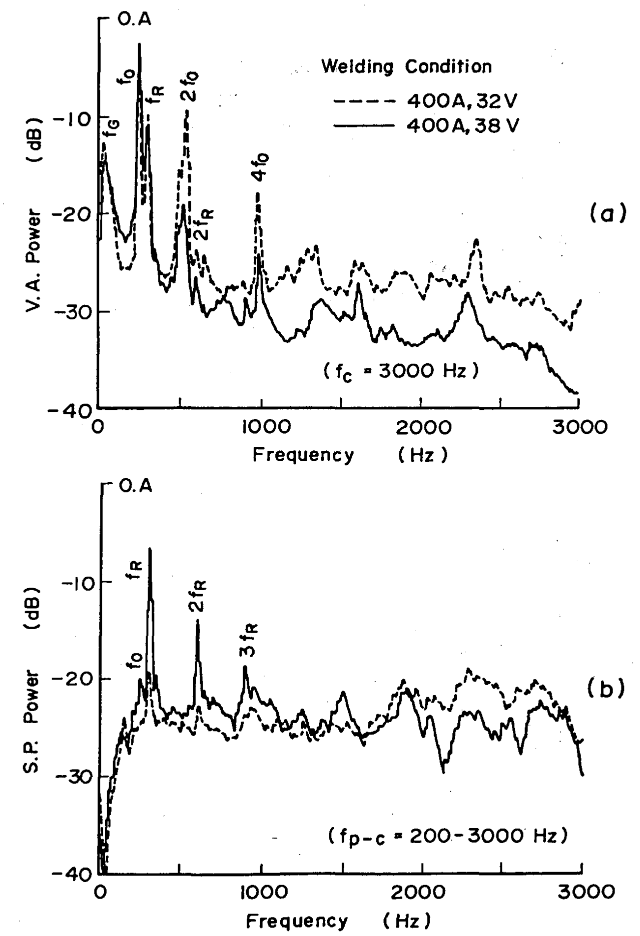

Fig. 8 Power spectrum of welding vibration (a) and welding arc sound (b) on Globular transfer arc at high frequency region.

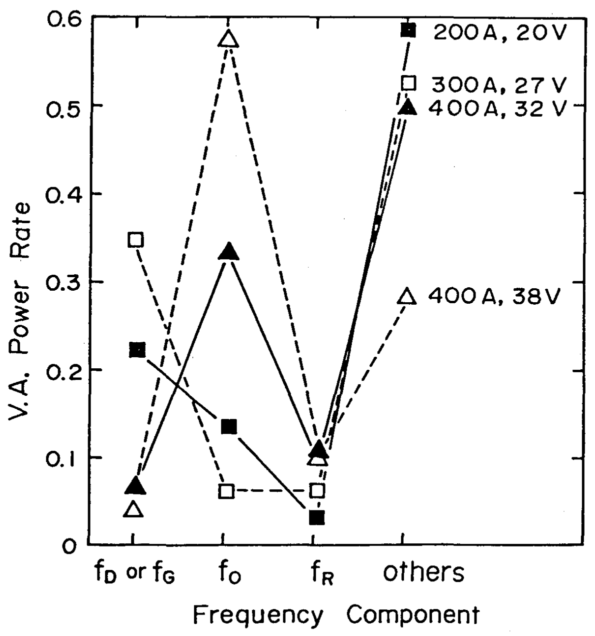

Fig. 9 Correlation between f_D (or f_G), f_R and f_0 components and vibration acceleration power rate.

whole. (f_D and f_G components did not appear owing to filtering.) In the case of welding vibration, components of high frequency region tended to decrease, being attenuated in the propagation process.

3.5 Results of frequency analysis of welding vibration (low frequency region)

Results of analysis of the waveform of welding vibration in low frequency region in the cases of conditions of Dip transfer arc and Globular transfer arc are shown in **Fig. 10** and **Fig. 11**. Results of frequency analysis of the waveform of welding current which is assumed to affect welding vibration because of its close correlation[6] with welding arc sound also shown in these Figures. The distinguished spectra near 35 Hz and 20 Hz in Fig. 10-(a) and -(b) are the components corresponding to f_D. The spectrum near 20 Hz in Fig. 11 -(a) and -(b) is the component approximately crresponding to f_G. No distinguished peak is ob-

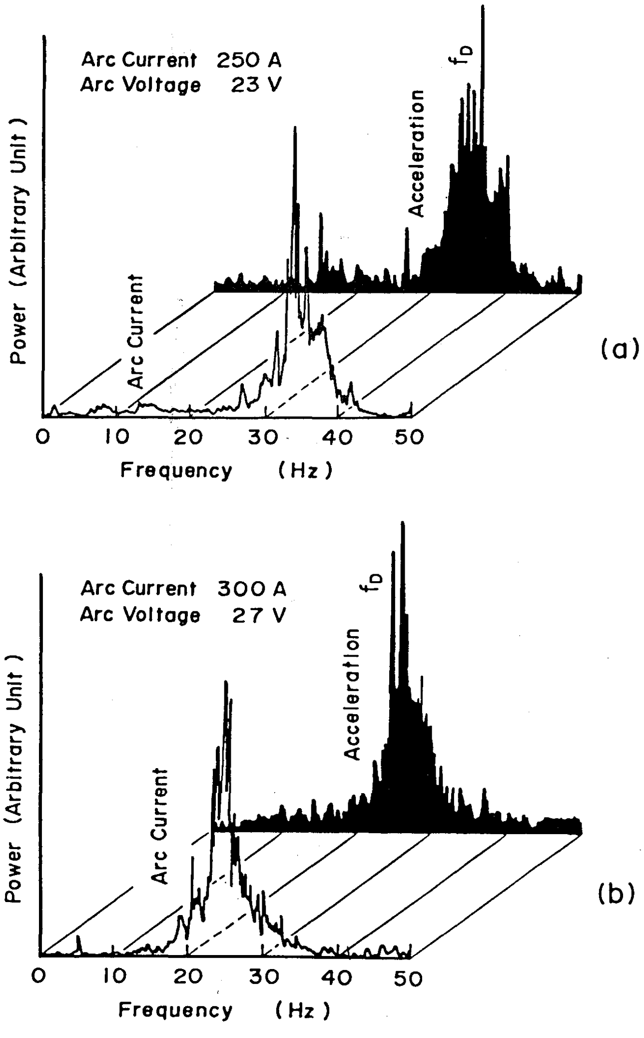

Fig. 10 Power spectrum of acceleration of welding vibration and welding current on Dip transfer arc at low frequency region.

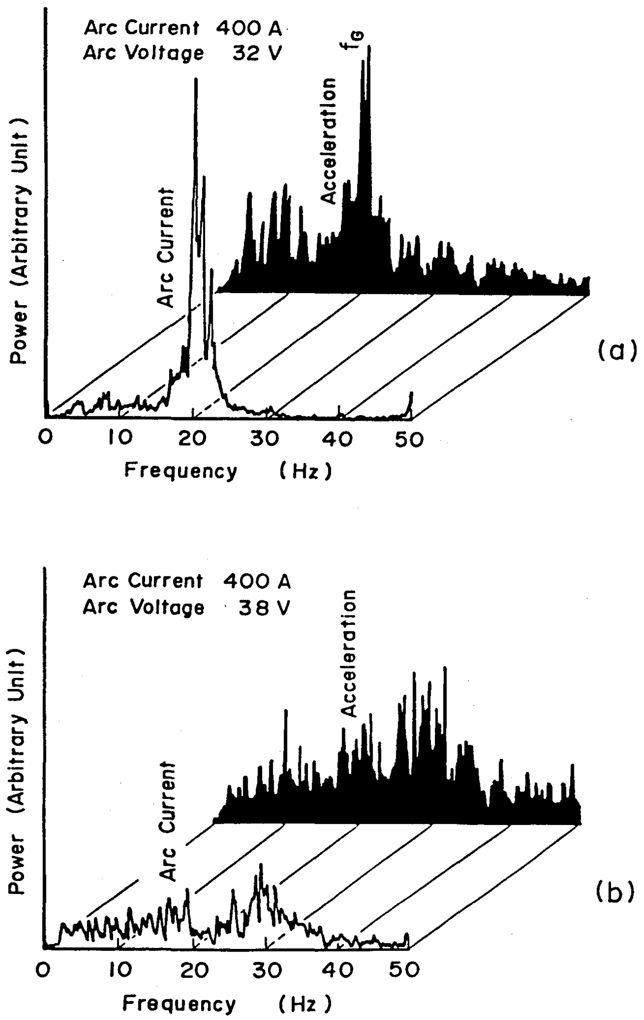

Fig. 11 Power spectrum of acceleration of welding vibration and welding current on Globular transfer arc at low frequency region.

served in Fig. 11-(b), which is in good agreement with the results shown in Fig. 2-(d) and Fig. 5-(b).

The profiles of frequency spectra of welding vibration and the waveform of welding current are similar very well to each other, which shows the existence of strong correlation between them in low frequency region. This result is in good agreement with Inoue et al's experimental result[7] that the vibration of the light of arc plasma in low frequency region corresponds to the variation of welding current from the view point of frequency. (The variation of the light of arc plasma depends on shortcircuit reignition of arc in the condition of Dip transfer arc and on the separation of droplets in the condition of Globular transfer arc). However, it is difficult in general to obtain informations concerning fine welding vibration for wide range from welding current because of the characteristic of the transient response of electric source.

4. Conclusion

Welding vibration was detected, its characteristics were clarified, and its correlation with the behavior of molten pool and the welding arc sound was studied. Results of the present experiment concerning CO_2 arc welding are summarized as follows:

(1) Welding vibration, especially that in low frequency region can be detected fairly accurately with a piezoelectric accelerometer of the sensibility of 100 mV/G class.

(2) VAL and SPL show a similar tendency of variation for wide range including the appropriate arc voltage, but they show different tendency of variation for the range of exessive arc voltage.

(3) The component f_D corresponding to the frequency of short-circuit reignition of arc, the component f_G corresponding to the frequency of the separation of droplets, the component f_R corresponding to the frequency of output current ripple, and the component f_o corresponding to the intrinsic frequency of material to be welded including the welding bench are observed in the frequency spectra of welding vibration similarly as in the case of welding arc sound. The three components f_D (or f_G), f_R and f_o occupy 50 to 70% of the intensity of total frequency components.

(4) The distinguished frequency spectra in low frequency region of welding vibration up to 50 Hz are the components f_D and f_G. The profiles of frequency spectra of welding vibration and welding current in low frequency region are similar very well to each other.

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