[Article ID] 1003 - 6326(2000)06 - 0712 - 05

Effects of arc-excited ultrasonic on microstructures and properties of weld①

ZHANG Chun-lei(张春雷), WU Min-sheng(吴敏生), HONG Yu-ping(洪玉萍), LI Lu-ming(李路明), ZHANG Yan-jun(张雁军)
(Department of Mechanical Engineering, Tsinghua University, Beijing 100084, P.R.China)

[Abstract] To control the solidification process of metal, a new method, arc-ultrasonic, was developed. A high-frequency exciting supply was electromagnetically coupled with conventional welding supply. An arc-excited ultrasonic emission was induced successfully in arc combustion process. Some signals with different frequencies and currents were used in submerged arc welding and CO_2 gas-shielded arc welding. The effects of arc-ultrasonic on the structures and properties of the weld (including the fusion zone, coarse grain zone and heat affected zone) were studied. The results show that more acicular ferrites form in the fusion zone, the toughness is improved under the arc-ultrasonic of different frequency, and the coarse microstructures in the partially melted zone is refined.

[Key words] arc-ultrasonic; refined grain; fusion zone; coarse grain zone; heat affected zone
[CLC number] TG401 **[Document code]** A

1 INTRODUCTION

The low toughness of the weld with coarse microstructures is an obstacle to manufacture welding configuration of high-performance. From the metallurgical concept, the microstructures can be refined by controlling the nucleation ratio and the grow rate of the crystal. There are two methods used generally. One is the chemistry method which adds alterant into the liquid metals[1,2]; however, refinement effect of the chemistry method is unconspicuous because of limit of addition amount and inhomogeneous distribution of the alterant. The other is the physics method[3~5]. In this method, special external physical field, such as vibration, agitation and wobble are employed to promote the motion of liquid metals during solidification in order to refine the microstructures. In these methods, power ultrasonic is regarded as an effective way[6,7].

However, up to now, ultrasonic energy of piezoelectric transducer and magnetostrictive transducer cannot be used in the welding process. On one hand, ultrasonic frequency, which usually depends on the structure parameters of the transducer, is difficult to adjust. Only when the resonance of key component such as concentrator (velocity transformer) in the vibration system occurs, ultrasonic energy can be generated and transmitted effectively. So the design, manufacture and adjustment of device are difficult, generally, changing ultrasonic frequency means replacement of the system hardware, which causes inconvenience for selection of the optimal frequency[8]. On the other hand, high-temperature erosion and cavitation erosion at the end of concentrator not only affects routine application of ultrasonic device, but also defiles the metal substrate and even forms some compounds which is unfavorable for improving the properties of the metals. In addition, since welding process is always done at high temperature, there is no effective way and proper coupler to transmit ultrasonic energy into the welding process.

In this paper, welding arc, due to its load characteristic in welding process, is used as a mechanism of ultrasonic emission. On the basis of welding parameters, arc is modulated to emit ultrasonic. The arc-excited ultrasonic, not only responses in wide range of frequency and is adjusted in real-time, but also couples itself directly to the weld-piece.

2 EXPERIMENTAL

The experimental system is shown in Fig.1. A half-bridge exciting source which can be adjusted from audio frequency to several hundred thousand Hz was designed. The exciting source can be coupled freely with conventional DC welding power supply of SAW (submerged arc welding) and CO_2 gas-shielded arc welding in parallel connection through transmitting line. PZT AE transducer of high-level sensitivity and microphone with high frequency response were used to record the ultrasonic signals from the workpiece and from the air, respectively. AE signals are sent to PC through a digital oscilloscope (TDS-210 type) and analyzed subsequently.

In the SAW process, Electrode wire (H08MnA type) with a diameter of 4 mm and granular flux

① **[Foundation item]** Project (59775061) supported by the National Natural Science Foundation of China
[Received date] 2000 - 04 - 09; **[Accepted date]** 2000 - 07 - 30

(HJ431 type) were used. Welding parameters were $U = 30\,V$ and $I = 500\,A$. In the CO_2 gas-shielded arc welding process, Electrode wire (H08 Mn2Si type) was used, and welding parameters were $U = 26\,V$ and $I = 160\,A$. The parameters of exciting source such as frequency, power and ON/OFF ratio of the switch can be adjusted freely in real-time according to the condition of welding process. In the paper, ON/OFF ratio of the switch was 1∶1.

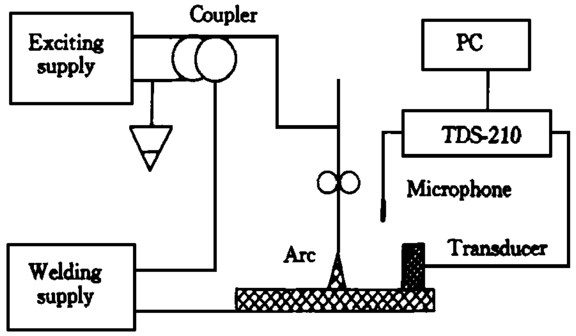

Fig.1 Schematic diagram of arc-ultrasonic system

The toughness samples were obtained according to GB2650-81. The sizes of the tested samples were 10 mm × 4 mm × 55 mm, the samples were tested at room temperature.

3 MICROSTRUCTURES AND PROPERTIES OF WELD

3.1 Fusion zone

The typical micrographs in the fusion zone of CO_2 gas-shielded arc welding are shown in Fig.2.

It can be seen from the experiment that under the action of arc-ultrasonic, the orientation of columnar microstructure in the fusion zone has changed, compared with that under conventional condition.

It can be seen from Fig.2 that, influenced by arc-ultrasonic, more acicular ferrite (AF) appears in the fusion zone during the phase transformation from austenite (γ) to ferrite (α), whereas more ferrites with grain-boundary (GBF) and side-plate (FSP) appear in the fusion zone during conventional welding process. Moreover, sizes of GBF and FSP of arc-ultrasonic welding are small. The difference in the microstructure leads to the difference in mechanical properties. It is well known that more AF can baffles the cracks to spread and improve the toughness of the weld.

Tables 1 and 2 are the experimental results of the Charpy V-notch toughness of the fusion zone. As we know, the toughness of the mild steel is steady. But in this experiment, the results show that the toughness of the fusion zone is improved at different degree when arc-ultrasonic of different frequency is transmitted into the weld. The toughness of the fusion zone can be improved much when arc-ultrasonic of 50 kHz is transmitted into the weld, because the external excitation resonates with the melted pool. The resonance mechanism was analyzed in detail in another paper[9]. Moreover, ultrasonic power has complex influence on the toughness of the fusion zone.

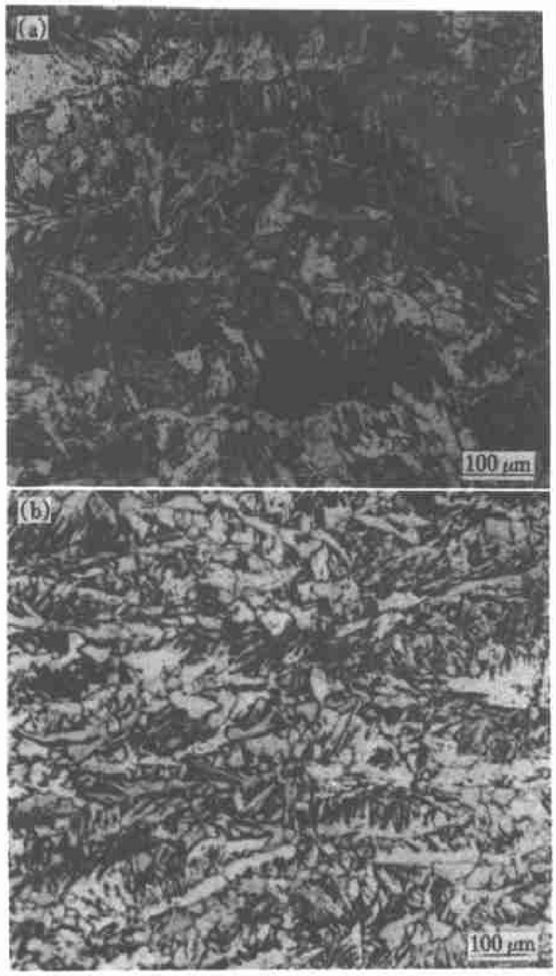

Fig.2 Typical micrographs in fusion zone of CO_2 gas-shielded arc welding
(a) — Without ultrasonic; (b) — With arc-ultrasonic

3.2 Partially melted zone (coarse grain zone)

The partially melted zone is a weak link of the heat affected zone in the conventional weld. The peak temperature in the partially melted zone during thermal cycle is usually above 1 300 ℃ since it is located immediately outside the fusion zone. In the partially melted zone, Widmanstätten microstructure often forms and the grain is coarse and the toughness is lower. The microstructures of the partially melted zone welded by conventional CO_2 gas-shielded arc welding are shown in Fig.3(a).

When ultrasonic energy is transmitted into the welding process, the microstructures of the partially melted zone change remarkably. When the modulation frequency of the exciting source is 50 kHz, the

Table 1 Toughness of fusion zone varying with modulation frequency

Modulation frequency / kHz	a_K / (J·cm^{-2})	Increment of toughness / %
Without ultrasonic	157	0
10	168.9	7.6
20	164.6	4.8
50	174.6	11.2
80	165.8	5.6
100	165.5	5.4
150	168.6	7.4
200	167.5	6.9

Modulation current: 20 A

Table 2 Toughness of fusion zone varying with modulation electric current

Modulation current/ A	Modulation frequency/ kHz	a_K / (J·cm^{-2})	Increment of toughness/ %
20	10	168.9	7.6
	20	164.6	4.8
	30	166.4	6.0
	40	174.6	11.2
40	10	167.0	6.4
	20	174.4	11.1
	30	168.8	7.5
	40	171.9	9.5
60	10	168.8	7.5
	20	162.5	3.5
	30	167.1	6.4
	40	168.1	7.1

coarse grain is refined notably, as shown in Fig.3 (b).

3.3 Heat affected zone (HAZ)

The morphologies of the SAW welds obtained with arc-ultrasonic exciting of different frequency are shown in Fig.4. It can be seen that the range dimension of HAZ increases with the increase of exciting frequency.

When the frequency is 80 kHz, the appearance of HAZ is exponent-shape and almost a "mirror" of arc force reflected in the substrate. Further micro-analysis of the weld reveals that increasing part of HAZ is mainly in the normalized zone, whereas the coarse grain zone is usually 0.9 ~ 1.0 mm. With the increase of arc-ultrasonic frequency, the width of the coarse grain zone almost maintains unchanged, and even decrease somewhat, which reduces the sensitivity of the toughness to welding line-energy.

Compared with conventional welding process, arc-ultrasonic excitation leads to the increase of welding line-energy. However, the current of arc-ultrasonic excitation is much smaller than welding current, that is, the direct effect of arc-ultrasonic is adding a smaller high-frequency pulse current into a much bigger welding current. It may be concluded that the change of HAZ is not caused directly from

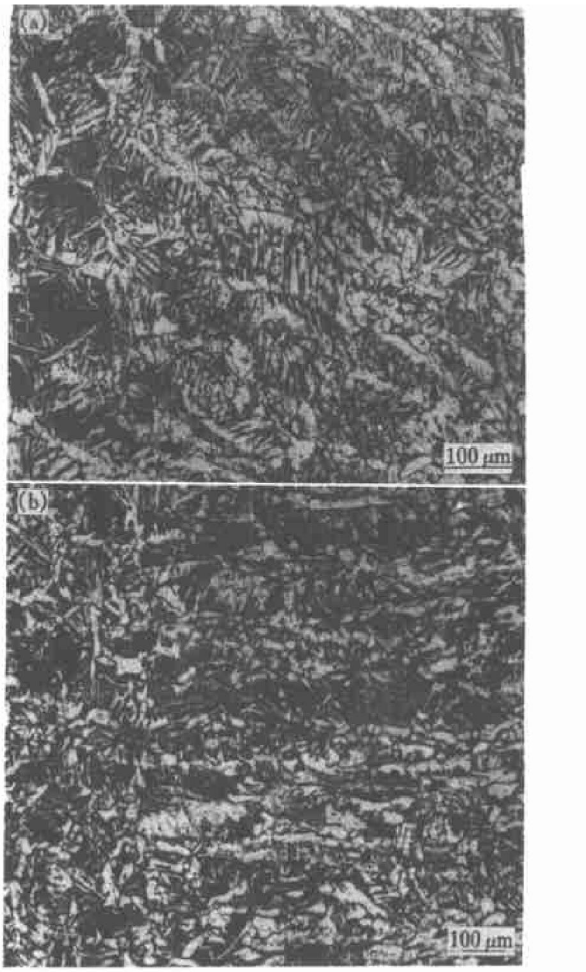

Fig.3 Typical micrographs in coarse grain zone of CO_2 gas-shielded arc welding
(a) — Without ultrasonic; (b) — With arc-ultrasonic

little change of welding line-energy, but is brought by ultrasonic effects induced by pulse action of exciting current, which is proved by the ultrasonic signals recorded by both of the AE transducer and the microphone in another way.

4 MECHANISM OF ARC-ULTRASONIC

4.1 Ultrasonic effects

The essence of arc-ultrasonic is that free arc or plasma arc is modulated by high-frequency ultrasonic source. The principle and sound characteristic of arc-ultrasonic were described in Ref.[10]. The welding current in the experiment is usually much bigger than the current of ultrasonic excitation. For example, in SAW process the welding current is 500 A, and arc voltage is 30 V, whereas the exciting current is 20 A only. Therefore, the external excitation does not influence basic parameters of conventional welding process. The role of arc-ultrasonic in the welding process does not rely on the modulation energy of the welding current or arc voltage, but rely on the frequency of excitation and other ultrasonic parameters

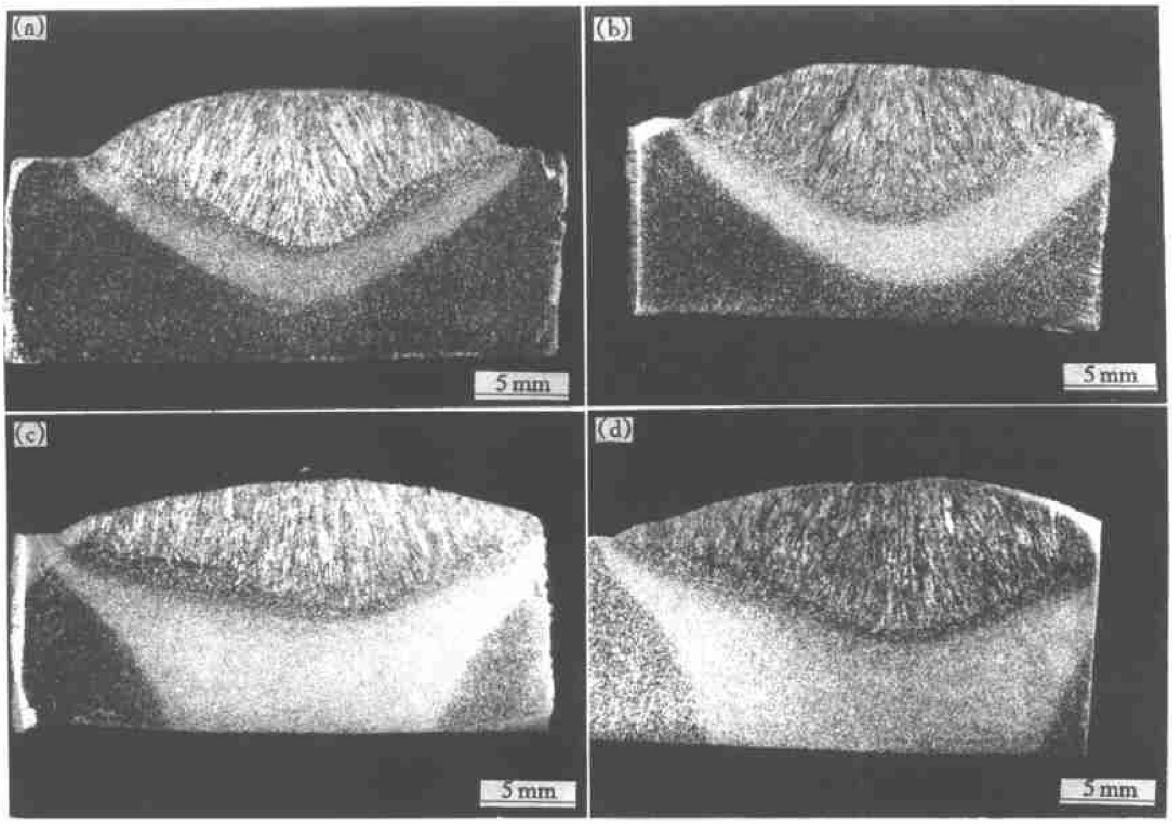

Fig.4 Morphologies of SAW welds with arc-ultrasonic exciting of different frequencies (modulation current 20 A)
(a) — Without exciting; (b) —30 kHz; (c) —50 kHz; (d) —80 kHz

such as ultrasonic amplitude, ultrasonic power, sound pressure and various effects in the liquid metals produced by these ultrasonic parameters.

As mechanical vibration, ultrasonic can bring several changes in both liquid and solid. 1) Due to the viscidity of liquid metals, ultrasonic energy may be absorbed by liquid and transferred into heat during propagation, which may increase the temperature of the liquid. The higher ultrasonic frequency and ultrasonic power are, the more notable the heat effect is. Hereby if the heat effect of ultrasonic is only considered, it is harmful to the weld with increasing ultrasonic frequency and ultrasonic power. 2) Mechanics parameters of ultrasonic such as displace, velocity and acoustic pressure maybe interact with liquid metals. In a certain range, the actions of ultrasonic vibration increase with the increase of ultrasonic frequency and ultrasonic power. The toughness of the weld in Tables 1 and 2 reveals the positive and negative action of ultrasonic frequency and ultrasonic power. Therefore, heat effect and mechanics effect must be taken into account synthetically when ultrasonic parameters are selected. 3) When tiny bubbles in the liquid are activated to oscillate, grow, shrink and collapse by ultrasonic, cavitation effect occurs. Cavitation effect can focus ultrasonic energy and release afterward with collapse of bubbles in a very short time and in a very small interspace, which generate intense shock waves in the liquid. According to Ref.[11], during the collapse of a cavity, the pressure increases to several GPa, and the temperature increases to several thousand Celsius degrees.

4.2 Influences of arc-ultrasonic on weld

The effects of arc-ultrasonic on the weld are in two ways. One is that ultrasonic energy can promote heat conduction remarkably, the other is that ultrasonic may disturb the solid/liquid interface and the motion of the liquid.

Ultrasonic vibration can make the boundary layer and laminar flow of the liquid metals distort, displace and torrent, which may promote the heat conduction in the liquid. Since the strength of the solid/liquid interface is very low at high temperature, the growing crystals can be broken down and the heat distribution in the liquid may be changed when the disturbance of ultrasonic vibration acts on the melt. Arc-ultrasonic disturbed natural development of GBF. The volume fractions of GBF and FSP decrease under action of arc-ultrasonic since GBF and FSP usually form at a higher temperature than AF.

When ultrasonic propagates through the substrate, the substrate may be compressed and expanded alternately, which leads to the periodical change of the substrate density. In the compressing area the volume of substrate decreases, which leads to the higher temperature. On the contrary, in the expanding area the volume of substrate increases, which leads to the lower temperature. The temperature gradient occurs between the compressing area and the expanding area, and heat flows from the area of higher temperature to the area of lower temperature, so it promotes the heat exchange and changes the temperature distribution, finally the range dimension of HAZ increases. During the heat conduction, ultrasonic energy is transferred to crystal lattice, that is, mechanical energy of ultrasound is transformed into heat energy which results in vibration of crystal lattice.

Arc plasma oscillates under modulation of external excitation and generates ultrasonic, whereas the effects of arc-ultrasonic on the melted pool reveal the value of periodical arc force. The amplitude of ultrasonic vibration is big and the ultrasound effect is strong along the axes of the arc, so the HAZ along the direction is deep. At sides of the axes of the arc, the amplitude of ultrasonic vibration decreases and the effect of heat conduction weakens, and the increase of the HAZ is smaller than that along the axes. If ON/OFF ratio of the switch maintains unchanged, the intensity of ultrasonic vibration increases and the effect of heat conduct strengthens with the increase of ultrasonic frequency. So the cross section of the HAZ is exponent-shape if the frequency of external excitation is high enough.

In addition, the direct of the biggest amplitude of ultrasonic vibration changes with motion of the torch. The solidification velocity of the weld is in proportion to the travel speed in welding process, and arc-ultrasonic has little influence on the liquid. On the contrary, arc-ultrasonic can disturb the coarse grain zone at the solid/liquid interface and promotes heat conduction in HAZ remarkably. Naturally, arc-ultrasonic has some influence on the solidifying metal at the back of the torch, but arc-ultrasonic must propagate through a distance. So arc-ultrasonic has different effects on different areas in the weld, which is one of arc-ultrasonic characters.

5 CONCLUSIONS

As a new way, arc-ultrasonic can coupled itself directly with work-piece and be transmitted in real-time into the welding process. It has obvious effects on various areas in the weld.

1) The microstructures in the fusion zone have changed under the actions of arc-ultrasonic with different frequency. More acicular ferrite appears and the toughness of the fusion zone is improved.

2) With arc-ultrasonic, the microstructures in the partially melted zone are refined.

3) The frequency of arc-ultrasonic has a great effect on the HAZ. Arc-ultrasonic of high frequency can increase the width of the temper zone and promote heat conduction notably.

4) The direction of the biggest amplitude of arc-ultrasonic is always along the axis of arc, so the ultrasonic field moves with the motion of the torch.

[REFERENCES]

[1] Li Hang, Chandel R S and Sritharan T. Effect of Al-Ti and Al-B master alloy addition on the grain refinement of stationary arc-melted Al weld [J]. J Mater Sci Lett, 1996, 15(21): 1886 - 1887.

[2] Dvornak M J, Frost R H and Olson D L. Influence of solidification kinetics on aluminum weld grain refinement [J]. Welding J, 1991, 70(10): 271 - 276.

[3] Abramov O V. Action of high intensity ultrasound on solidifying metal [J]. Ultrasonic, 1987, 25(2): 73 - 82.

[4] Tewari S P. Influence of vibration on grain size and degree of grain refinement in mild steel weldments [J]. J Mater Res, 1980, 11B(8): 467 - 473.

[5] Szekely J. Flow phenomena mixing and mass transfer in argon-stirred ladles [J]. Iron Making & Steel Making, 1979, 10(6): 285 - 292.

[6] Flemings M C. Behavior of metal alloys in the semisolid state [J]. Metal Trans, 1991, 22B: 269.

[7] LI Ying-long, LI Bao-mian, LIU Yong-tao, et al. Effect of high-intensity ultrasonic on structures and properties of Al-Si alloys [J]. The Chinese Journal of Nonferrous Metals, (in Chinese), 1999, 9(4): 719 - 722.

[8] Timothy M. Practical Sonochemistry: User's Guide to Applications in Chemistry and Chemical Engineering [M]. New York: Ellis Horwood, 1991. 90-91.

[9] WU Min-sheng, ZHANG Chun-lei and DUAN Xiang-yang. Investigation of the frequent characteristic and the resonant mechanism of arc-excited ultrasonic [J]. Journal of Tsinghua University, (in Chinese), 1999, 39(11): 97 - 99.

[10] WU Ming-sheng, WANG Zheng-xian, LI Lu-ming, et al. Study on mechanism of arc-excited ultrasonic [J]. Chinese Journal of Mechanical Engineering, 1999, 12(1): 1 - 3.

[11] Rozenberg L D. Physical principles of ultrasonic technology (Vol. 2) [M]. New York: Plenum Press, 1973. 261.

(Edited by YANG Bing)