Arc Characteristics of Ultrasonic Wave-Assisted GMAW

The arc characteristics vary when an ultrasonic wave is added to the gas metal arc welding process

BY C. L. FAN, C. L. YANG, S. B. LIN, AND Y. Y. FAN

ABSTRACT

Ultrasonic wave-assisted gas metal arc welding (U-GMAW) is a newly developed welding method. Under the action of the ultrasonic wave, the characteristics of the welding arc make an obvious change. Compared with the conventional GMAW arc, the U-GMAW arc is more contracted and becomes brighter, and its length is decreased. The arc length varies wavelike with the height of the ultrasonic radiator. The reason is that the amplitude of the stationary ultrasonic wave pressure varies with the phase difference between the incident wave and the reflected wave. Under the same conditions, the ultrasonic energy and the contraction degree of the arc are enhanced with the increase in the diameter of the ultrasonic radiator and the ultrasonic vibration amplitude. In addition, the arc length in both GMAW and U-GMAW increases with increasing voltage. But at the same voltage, the arc length in U-GMAW is shorter than with GMAW, and the difference increases with the increasing voltage. For U-GMAW, the unit increase in arc length with increased voltage is only about one-third that of conventional GMAW.

Introduction

Gas metal arc welding (GMAW) has been widely employed in manufacturing, and has attracted extensive attention due to its advantages, which include high efficiency, high flexibility, and adaptability for welding most metals (Ref. 1). The stability and quality of GMAW is highly related to metal transfer, which is affected by many factors (Refs. 2, 3). Therefore, controlling and getting the ideal metal transfer is still a challenge. Many researchers have done some distinctive work in this field. In Ref. 4, a new method to employ the melting rate, heat input, and detaching droplet diameter as controlled variables to control heat and mass transfer was proposed. The Trifarc method used an extra wire with reversed electric current, which was inserted between the electrodes of the standard to control the molten droplet and pool (Ref. 5). In Ref. 6, the researchers struck an additional arc on the droplet, which served as the cathode to regulate the current distribution and metal transfer. Y. M. Zhang and others (Refs. 7–10) decoupled the undesired dependence of the metal transfer on the welding current and used a laser to facilitate droplet detachment from the wire tip. In addition, plasma diagnostics (Ref. 11), arc light and spectrum (Refs. 12, 13), magnetic field (Ref. 14), mechanical vibration (Refs. 15, 16), and arc sound (Refs. 17, 18) also have been used to control the metal transfer process.

In Refs. 19 and 20, the authors proposed a new hybrid welding method, ultrasonic wave-assisted gas metal arc welding (U-GMAW). During the U-GMAW process, ultrasonic radiation force was used to control the metal transfer. The experimental results showed the dimension of the droplet decreased and the transfer frequency increased, which led to deeper welding penetration and finer grain crystallization. The welding arc has important influences on the metal transfer process; however, the characteristics of the welding arc in the novel U-GMAW process have not been systematically studied and discussed.

It is well known that the arc is the ultimate source of the welding process and has the decisive influence on metal transfer as well as fusion of the base metal. During this research, it was also found that the ultrasonic wave not only had an obvious effect on the metal transfer but also on the welding arc. Under the action of the ultrasonic wave, it was obvious that the arc contracted and its energy density increased. The purpose of this study is to reveal the relationship and the action mechanism of the main ultrasonic parameters on the welding arc, such as the distance between the ultrasonic radiator and the workpiece, the ultrasonic vibration amplitude, and the action area of the ultrasonic radiator. The results are helpful in comprehensively understanding the U-GMAW method.

C. L. FAN (fclwh@hit.edu.cn)*, C. L. YANG, and S. B. LIN* (sblin@hit.edu.cn) *are with the Stake Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin, China. Y. Y. FAN is with Dongfang Electric Machinery Co., Ltd., Deyang, China.*

KEYWORDS

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Experimental Setup and Parameters

Experimental Setup

The U-GMAW system includes three components, i.e., an ultrasonic power source, a welding power source, and a hybrid welding torch, as shown in Fig. 1 (Ref. 19). The main body of the torch can be divided into two parts, i.e., the ultrasonic transducer and the ultrasonic horn. The ultrasonic transducer transforms electric energy into ultrasonic vibration, and then the vibration is amplified by the ultrasonic horn. The ultrasonic wave radiates out from the end of the ultrasonic horn (ultrasonic radiator in Fig. 1). The welding wire is fed through the axial hole of the transducer and the horn, and the arc is ignited between the wire tip and the workpiece. Since the wire does not contact any vibrating component, no vibration is conducted directly from the wire to the arc.

In order to conveniently observe the arc, bead-on-plate welding experiments were conducted. During welding, the workpiece also acts as the ultrasonic reflector. Since the dimension of the workpiece is much larger than the ultrasonic radiator, the workpiece can be regarded as

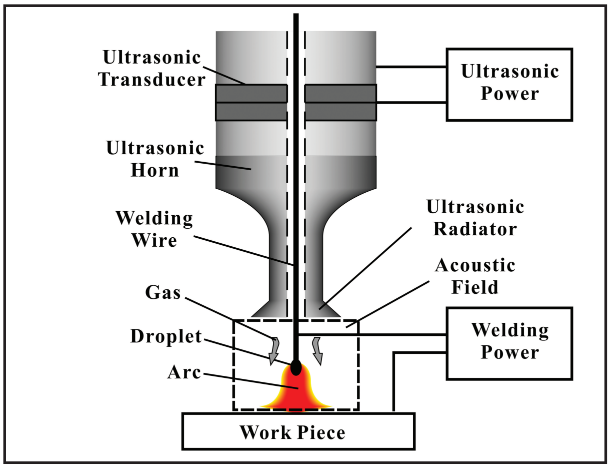


Fig. 1 — Schematic of U-GMAW (Ref. 19).

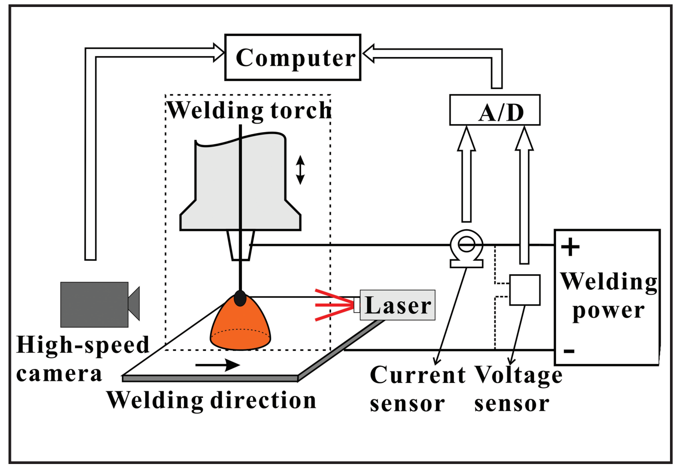


Fig. 2 — Schematic diagram of the experiment system.

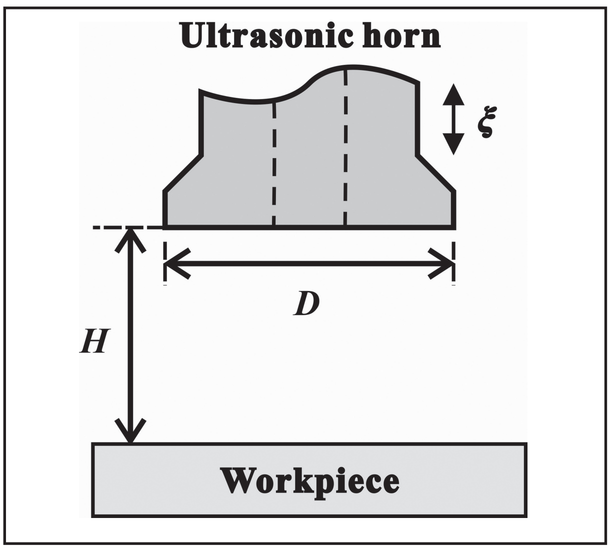


Fig. 3 — Parameters of the ultrasonic system.

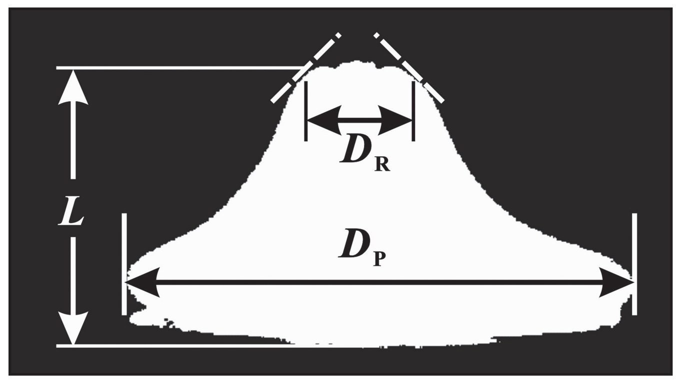


Fig. 4 — Parameters of the arc shape.

an ideal infinite reflector. With the reflection, a stable interference acoustic field is formed between the radiator and the workpiece, and the arc is burning inside this acoustic field.

The ultrasonic power source was a CSHJ-1000 with the output power of 1000 W. A digital control, constant voltage power supply (Kemppi, Promig 500) was employed, and the welding process was performed under the direct current electrode positive (DCEP) condition. During the experiments, the welding torch was fixed and the workpiece was moved at a constant speed. The base metal was mild steel, and 1.2-mm-diameter ER70S-6 wire was chosen as the electrode. Pure argon was used as the shielding gas. The other welding parameters are shown in Table 1.

High-speed photography and a laser shadowing method were used to investigate the welding arc, as shown in Fig. 2. The camera was an Optronis CamRecord D5000×2. The wavelength of the laser beam used as the back light is 808 nm, and a bandpass filter with the same wavelength was mounted in front of the lens to strain off the arc light. With a shutter speed of 20 μs, the camera's frame rate is 3000 f/s at an image resolution of 512 × 512 pixels.

Experimental Parameters

There are four main ultrasonic parameters related to the experiments, i.e., f (ultrasonic frequency), H (distance between the ultrasonic radiator and the workpiece), ξ (ultrasonic vibration amplitude), and D (diameter of the ultrasonic radiator), as shown in Fig. 3. In this study, according to the frequency of the ultrasonic piezoelectric transducer, f was fixed at 20 kHz. The working voltage and current of the ultrasonic power were 220 V and 0.5 A, respectively. Of all these parameters, f and ξ are mainly concerned with the state of the incident wave.

The characteristic parameters of the arc shape are L (arc length), D_p (projected diameter), and D_R (root diameter) (Ref. 21), as shown in Fig. 4. During the GMAW process, because of the interference of the metal transfer, the arc shape is not invariable. Many factors, such as the form and transition of the droplet, have influence on it. By long-term observation, it was found that during a droplet transition period, D_p and D_R were changed violently while the variation of L was very slight. Therefore, in the following study, L is selected as the main characteristic parameter to indicate constriction of the arc.

Table 1 — Experimental Parameters

Wire Feed Speed (wfs, m/min)	Welding Voltage (V)	Welding Speed (mm/min)	Flow Rate of the Shielding Gas (L/min)	Distance from the Contact Tube to the Workpiece (mm)	Distance from the Nozzle to the Workpiece (mm)
3.5	27	300	25	24	11

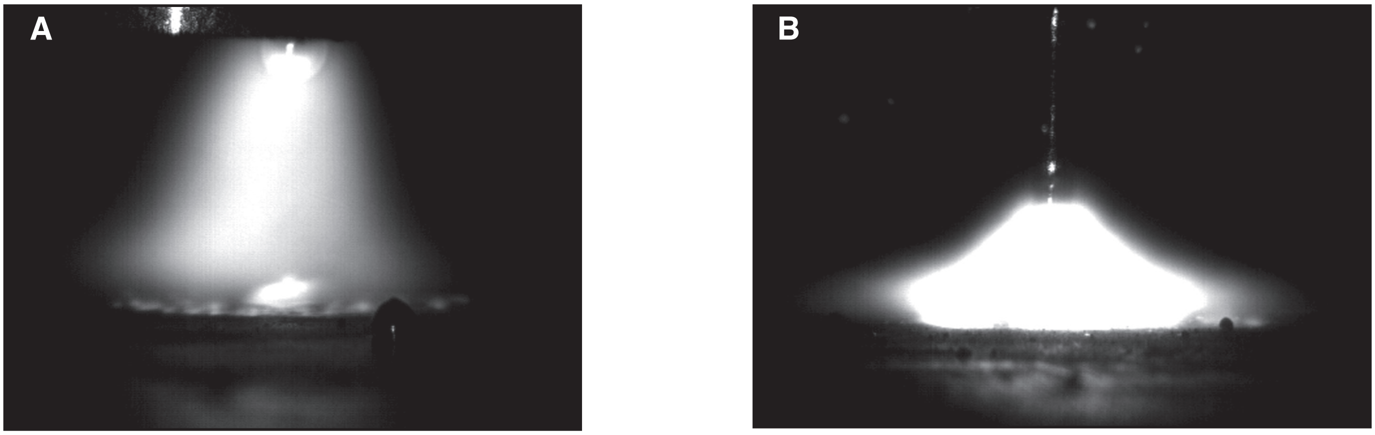


Fig. 5 — Comparison of conventional GMAW and U-GMAW arcs. A — Conventional GMAW arc; B — U-GMAW arc.

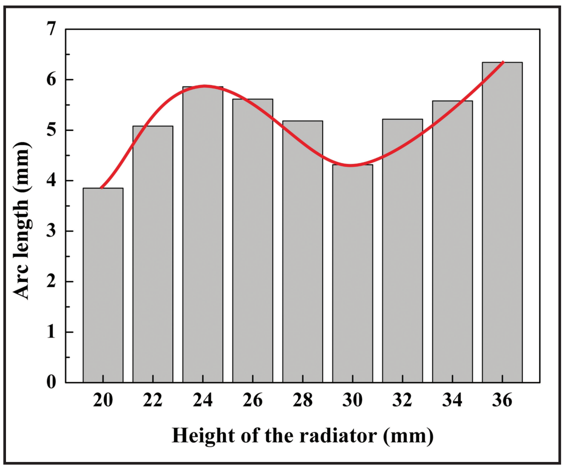


Fig. 6 — Relationship between H and L.

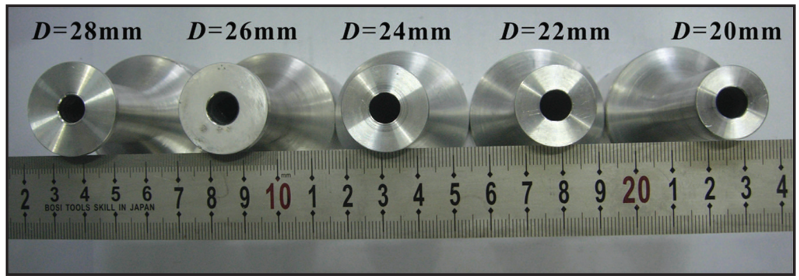


Fig. 7 — Ultrasonic horns with different end diameters.

Results and Discussion

The Effect of the Ultrasonic Parameters

The Distance between the Ultrasonic Radiator and the Workpiece

Figure 5 shows the differences between the conventional GMAW arc and the U-GMAW arc. From the figures, it can be seen that compared with conventional GMAW, the U-GMAW arc is contracted and becomes brighter. The relationship between L and H is shown in Fig. 6, and the fitting curve is wavelike rather than linear, which typically represents the influence of the acoustic field. It can also be seen that the contraction degree of the U-GMAW arc varies with H. Under the H of 20 and 30 mm, the arc is shorter than that under the other H values.

The incident ultrasonic emitted from the radiator can be expressed as wave Equation 1 (Ref. 22):

$$p_i = p_A \cos(\omega t - \phi_1) \quad (1)$$

where p_i is the ultrasonic pressure, p_A is the amplitude of p_i, ω is the angular frequency, t is time, and φ_1 refers to the initial phase of the ultrasonic wave.

When the incident ultrasonic wave hits the reflector (the workpiece) surface, the reflected wave is generated. If neglecting the attenuation of the ultrasonic wave, the reflected wave can be expressed as Equation 2, where p_r is the reflected wave pressure, φ_2 is the phase of the reflected ultrasonic wave, and $\varphi_2 = \varphi_1 + \psi$. ψ is the phase difference between the incident wave and reflected wave.

$$p_r = p_A \cos(\omega t + \varphi_2) \quad (2)$$

The virtual ultrasonic field between the ultrasonic radiator and the workpiece is the interfered result of the incident ultrasonic wave and the reflected ultrasonic wave, which can be called the stationary acoustic field. This field is given in Equations 3 and 4, where p_C is the amplitude of the stationary ultrasonic wave pressure, and φ refers to the phase of the stationary ultrasonic wave.

$$p = p_i + p_r = p_C \cos(\omega t - \varphi)$$
$$p_C^2 = 2p_A^2 + 2p_A^2 \cos(\psi) \quad (3)$$

$$\varphi = \arctan \frac{\sin\varphi_1 + \sin\varphi_2}{\cos\varphi_1 + \cos\varphi_2} \quad (4)$$

From the equations, it can be seen that the stationary ultrasonic wave is still an ultrasonic wave with the same vibration frequency as the incident ultrasonic wave. The amplitude of the stationary ultrasonic wave depends on the phase difference (ψ) between the incident wave and the reflected wave, instead of the algebraic sum of their absolute values.

The most important influence factor of ψ is the distance between the radiator and the workpiece, i.e., H. Under some specific H values, ψ is even multiple times of π. The incident ultrasonic wave and the reflected wave reach the peak value simultaneously, and the stationary ultrasonic wave has double amplitude of the incident ultrasonic wave where the stationary acoustic field is a syntonic field with the maximum energy density. While under some other specific H values, ψ is odd multiple times of π, the incident ultrasonic wave and the reflected wave canceled out, which means the amplitude of the stationary wave is zero and the ultrasonic field energy density is minimum.

The particles inside the normal arc, such as the electrons and ions, are moved by the drive of the electric field between the anode and cathode. But the situation changed inside the U-GMAW arc; the additional ultrasonic wave will influence the motion state of the particles. Beside the motion caused by the electric field, the particles are forced to oscillate around their equilibrium position 20,000 times per second. This vibration increases the instantaneous velocity and the collision

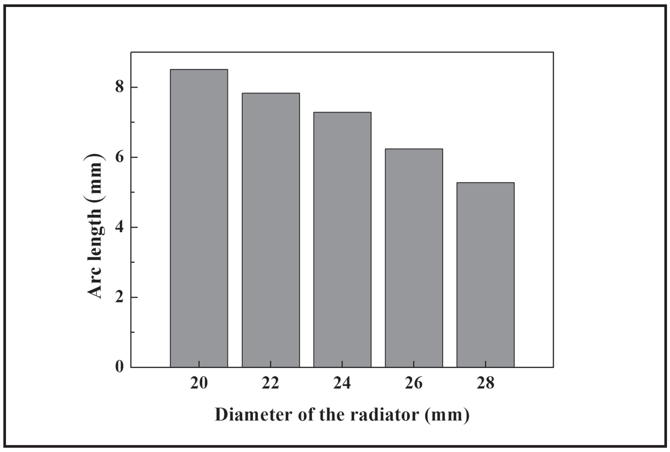


Fig. 8 — Relationship between D and L.

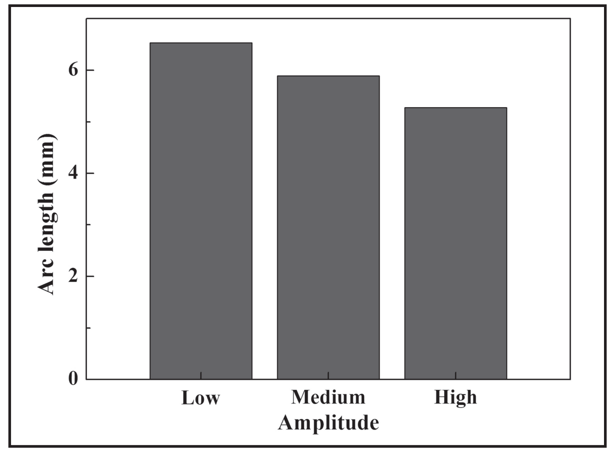


Fig. 9 — Relationship between ξ and L.

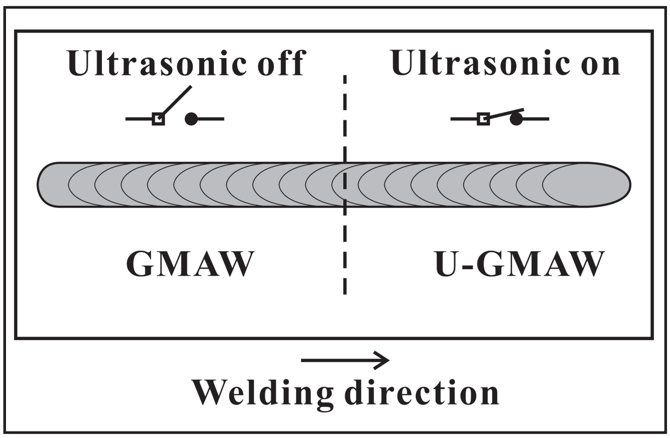


Fig. 10 — Schematic of the comparative experiment.

probability of the particles, which will surely increase their thermal conductivity. In other words, more heat will be transferred to the workpiece, and this will break the equilibrium of the general heat production and dissipation. According to the principle of minimum voltage (Ref. 2), the arc has to constrict to reduce the heat loss. On the other side, the arc must increase the electric field strength to remain the increasing particle collision probability and generate more heat to compensate for the heat loss. The increasing electric field strength leads to the increasing power density along the arc, and that is why the U-GMAW arc is brighter than the GMAW arc. A similar phenomenon has also been observed during ultrasonic-assisted gas tungsten arc welding (U-GTAW) (Ref. 23). However, the arc length in the GTAW process is stable between the nonconsumable electrode and the workpiece. This is different from the U-GMAW process.

If the H value is changed continuously, as shown in Fig. 6, ψ will vary synchronously, which causes continuous variation of the stationary acoustic field energy density. Under some certain H values (e.g., H = 20 or 30 mm), the incident ultrasonic wave and the reflected wave resonated, and the stationary acoustic field reaches to the maximum energy density, thus the constriction degree of the arc reaches to the peak value.

From Fig. 6, it can be seen that when the H value equals 20 or 30 mm, the contraction degree of the arc reaches maximum, and the arc length is only about 43–48% of that of the conventional GMAW arc (Fig. 5A), respectively, and the variation curve of the L-H reaches the trough area.

Though the degree of arc contraction is maximized under the condition of H = 20 or 30 mm (a little bit weaker when H = 30 mm), but from the welding point, H = 30 mm is much better. That's because during the GMAW process, spatter is unavoidable, and if spatter attaches on the radiator surface, it would affect the emission of the ultrasonic wave, so a higher H value is more reasonable. Otherwise, a smaller H means the horn is closer to the arc and the temperature of the horn is higher, which will weaken the stability and efficiency of the ultrasonic radiation.

<u>Diameter of the Ultrasonic Radiator</u>

In order to test the influence of the ultrasonic radiator dimension on the arc, five horns with different end diameters (D) were machined, as shown in Fig. 7. For the limit of the spray nozzle dimension, the largest D was 28 mm. The test results are showed in Fig. 8.

In Fig. 8, the arc length reduced monotonously with the increase in D. Higher D means a larger radiation area, which surely would improve the ultrasonic energy density and the degree of arc contraction. In addition, the degree of arc contraction was greater when D changed from 24 to 28 mm than when it changed from 20 to 24 mm. That's because when D was at a higher level, the increase in the annular radiation area caused by the same increasing diameter was higher.

<u>The Ultrasonic Vibration Amplitude</u>

The ultrasonic system has three levels of vibration amplitudes, i.e., ξ = 25, 28, and 30 μm. Figure 9 shows the influence of the vibration amplitudes on the welding arc. The degree of arc contraction increased with the increasing vibration amplitude, but compared with H and D, the effect of the ultrasonic vibration amplitude was not very strong.

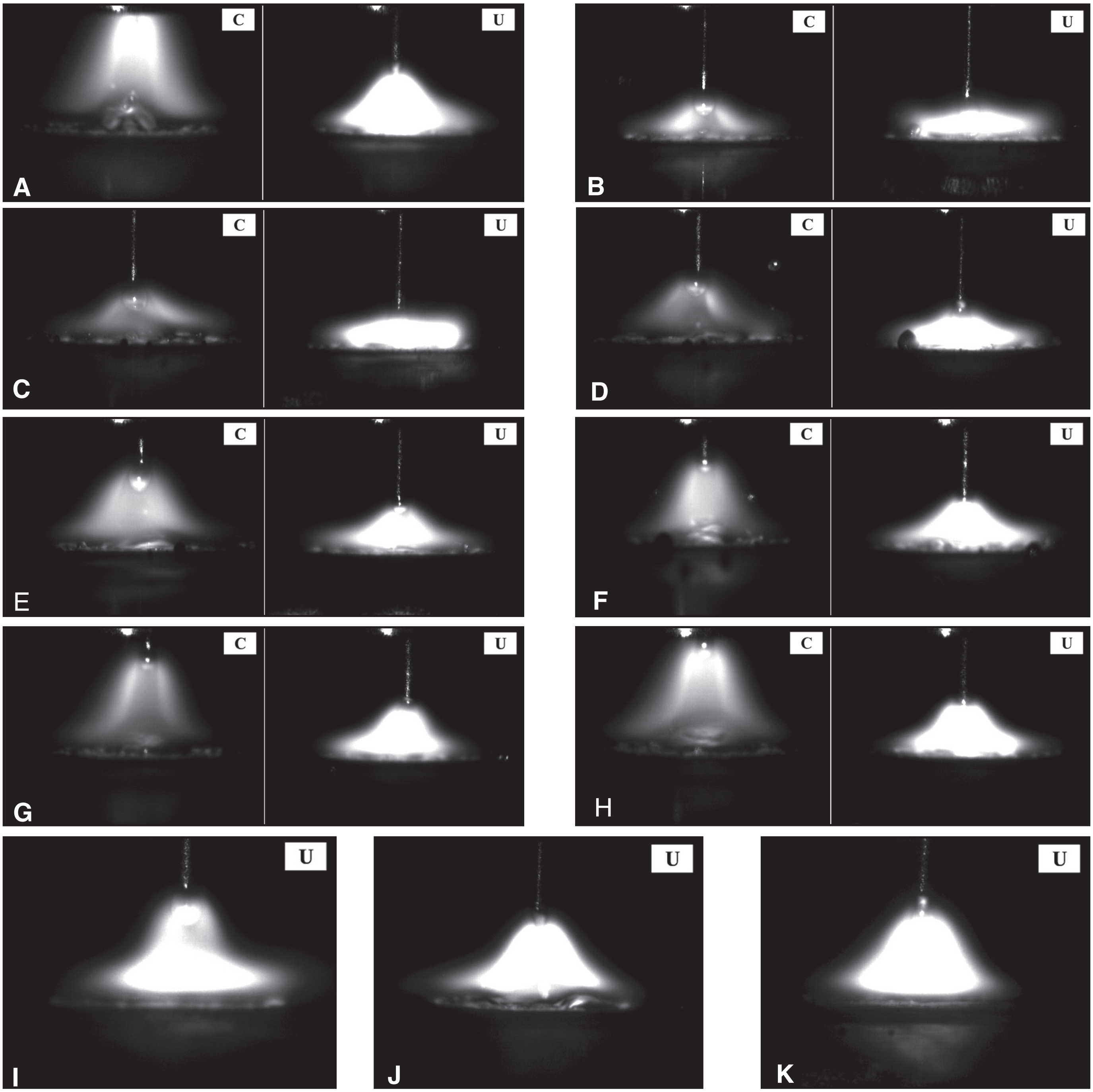
The level of the ultrasonic vibration amplitude indicates the degree that the particles are forced to oscillate around their equilibrium position, so it is not difficult to understand that greater ξ causes higher arc contraction.

The Effect of the Arc Voltage

In order to find out the influence of the arc voltage, a series of experiments was done based on the conditions of H = 30 mm, D = 28 mm, and H = 30 m. In order to ensure the same conditions for GMAW and U-GMAW, the test was taken on the same workpiece, as shown in Fig. 10. At the middle of the process, the ultrasonic wave was applied.

The arcs of conventional GMAW and U-GMAW at different welding voltages are showed in Fig. 11, and their differences are summarized as follows:

1. At the same voltage, the arc of U-GMAW is invariably shorter than that of GMAW, and the difference in length increases with the increasing voltage. In addition, the U-GMAW arc is distinctly



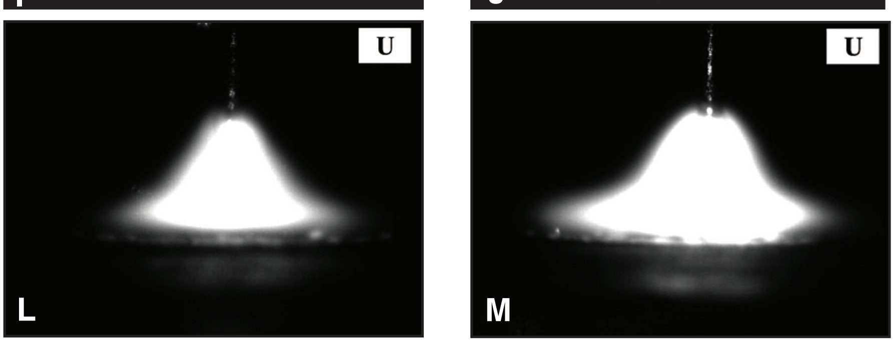


Fig. 11 — Arc shape at different welding voltages (wire feed speed (wfs) = 4.5 m/min; C stands for conventional GMAW; U stands for U-GMAW). A — 21 V; B — 22 V; C — 23 V; D — 24 V; E — 25 V; F — 26 V; G — 27 V; H — 28 V; I — 29 V; J — 30 V; K — 31 V; L — 32 V; M — 33 V.

brighter and more stable.

2. Arc length for both conventional GMAW and U-GMAW increased with the increasing welding voltage, but the growth rate of the conventional GMAW arc length is much higher than that of the U-GMAW arc. When the welding voltage reached 28 V, the conventional GMAW arc approached the nozzle (Fig. 11H). If the voltage increased continuously, the arc would retreat into the nozzle and damage the welding torch. In contrast, the U-GMAW arc remained a reasonable length within a large voltage range, even when the voltage reached 33 V. This is why only U-GMAW arc pictures were given when the voltage went beyond 28 V.

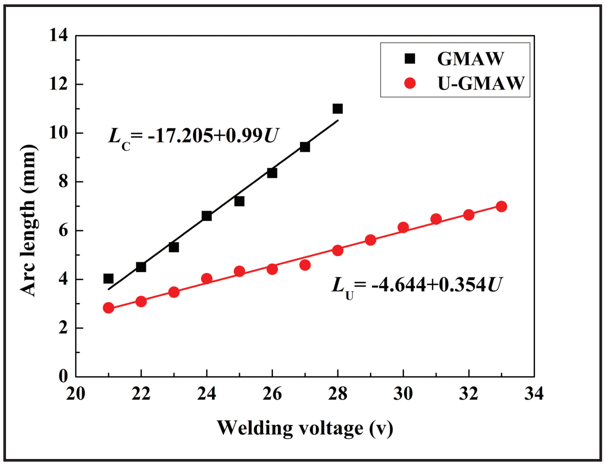


Fig. 12 — Relationship between welding voltage (U) and L.

Figure 12 reveals the relationship between the arc length and the welding voltage. Both the fitting curves of conventional GMAW and U-GMAW are linear. The fitting curve equations presented in the figure show that for conventional GMAW, the unit increase of the arc length is about 0.99 mm/V, while for U-GMAW, it is about 0.35 mm/V, which is only about one-third that of the former. Also, it can be deduced that the sum of cathode and anode fall voltages in U-GMAW is about 4.3 V less than that in the GMAW process.

In the experimental conditions, the welding material and the plate material are both low-carbon steel, which is a cold-cathode material. So, the electrical particle emission mechanisms are mainly electric field and collision emissions. In the experiments, the welding current was small, no more than 200 A. In the GMAW process, the particle collision could not provide enough charged particles. As a result, a high voltage was needed to establish a strong electric field, and the electric field emission could help maintain the stability of the welding arc.

In the U-GMAW process, the welding arc is compressed and the electric field intensity is improved. As a result, the particles in the arc are accelerated, and the collision is more intense. More charged particles are provided in the collision emission process, so that the sum of the anode and the cathode voltage is reduced in the U-GMAW process.

Conclusions

1. Under the action of the ultrasonic wave, the U-GMAW arc is contracted and brighter and its length is decreased. The arc length varies wavelike with the height of the radiator, but enhances with the increasing diameter of the radiator and the ultrasonic vibration amplitude monotonously.

2. The amplitude of the stationary ultrasonic wave pressure is associated with the phase difference (ψ) of the incident wave and the reflected wave. Sometimes when ψ is even multiple times of π, the contraction degree of the arc reaches maximum; when ψ is odd multiple times of π, the contraction degree of the arc is negligible.

3. The arc length of both conventional GMAW and U-GMAW increases with increasing voltage. At the same voltage, the arc length of U-GMAW is invariably shorter than that of GMAW, and the difference increases with the increasing voltage. For U-GMAW, the unit increase of the arc length to the voltage is only about one-third that of conventional GMAW.

Acknowledgments

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