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ORIGINAL ARTICLE

Arc character and droplet transfer of pulsed ultrasonic wave-assisted GMAW

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Abstract
Pulsed ultrasonic wave is employed to interfere the GMAW process, and the new method is named as pulsed ultrasonic wave-assisted GMAW (PU-GMAW). A controllable periodic ultrasonic resonant field has been established in the arc space, and the periodic ultrasonic radiation force was used to improve the arc energy density and to promote the droplet transfer. It was found that compared with GMAW, under the action of 6 Hz pulsed ultrasound, the arc shape was changed to conical shape, and the arc length was compressed to 53%. The diameter of the droplet decreased from 1.83 mm of GMAW to 1.3 mm of 6 Hz PU-GMAW, and the droplet diameter reduced 29%. The retaining time of the droplet at the end of the wire decreased and the flying velocity increased obviously, which induced the transition frequency of 6 Hz PU-GMAW reach to 285 Hz and that is two times of conventional GMAW. The pulsed ultrasound also has deep influence on the weld formation. The aspect ratio of the welding seam increases from 0.19 (GMAW) to 0.27 (6 Hz PU-GMAW), and the increasing rate is up to 37%. It has been ascribed that under the action of the ultrasound, the arc energy density increased and the heat is easily to be transferred to the bottom of the molten pool.

Keywords Pulsed ultrasound · Arc shape · Droplet transfer · Weld appearance

1 Introduction

Gas metal arc welding (GMAW) [1–3], characterized by high-welding efficiency, nice welding joint performance, and easy to realize automation, is widely used in industrial production. During GMAW, droplet transfer is a determining factor for the process stability and welding quality [4–6]. The droplet transfer process is brief and complicated, so droplet size, transition frequency, transition stability, and transition directivity must be considered comprehensively.

In the past few decades, the researchers endeavored to achieve better welding quality by controlling droplet transfer. As well known, the droplet is on the dynamic force equilibrium state [7], so when an additional force acts on the droplet, as shown in Fig. 1, it will surely break the force balance and promote/impede the droplet transfer. The key is the choice of the additional force. Gao et al. [8] investigated the arc characteristics and droplet transfer of laser-MIG hybrid welding. Campana et al. [9] studied the optimal position between the laser and the arc during laser-MIG hybrid welding process. Both of them pointed out that the filler metal transfer mode has significant influence on the stability of the welding process. Huang et al. [10] applied a low-power laser to droplets to generate an auxiliary detaching force and found that the auxiliary detaching force could promote droplet transfer. Kang et al. [11] used electromagnetic arc oscillation to improve the welding characteristics and arc signal in narrow groove gas metal arc welding. Zhang et al. [12] applied the external longitudinal magnetic field to laser-MIG hybrid welding to improve arc plasma characteristics and droplet transfer process. Pickin et al. [13] studied the cold metal transfer (CMT) process for welding aluminum alloy. Research shows that in comparison with pulsed metal inert gas (MIG) welding, mechanical vibration of wires exhibits a higher electrode melting coefficient during CMT process.

In previous study, Fan et al. [14] demonstrated that the ultrasonic radiation force (URF) can be used to promote the droplet transfer, and a new kind of ultrasonic wave-assisted GMAW (U-GMAW) was brought forward. During the U-GMAW, the ultrasonic wave and the welding arc are coaxial

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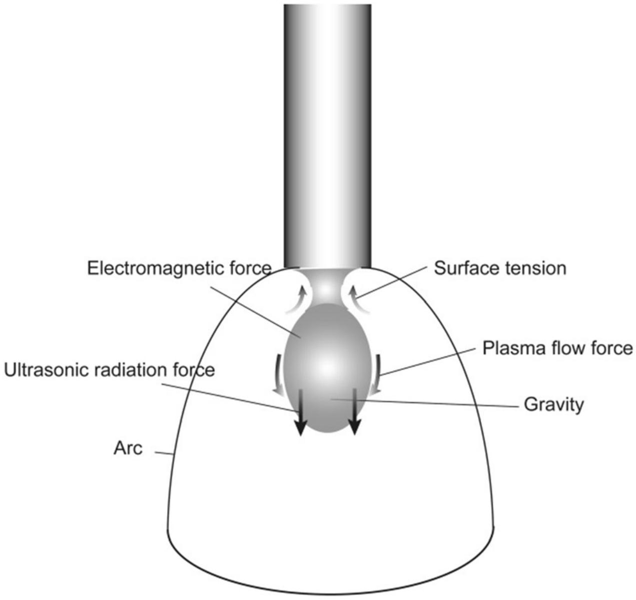

Fig. 1 Mechanics analysis of droplet

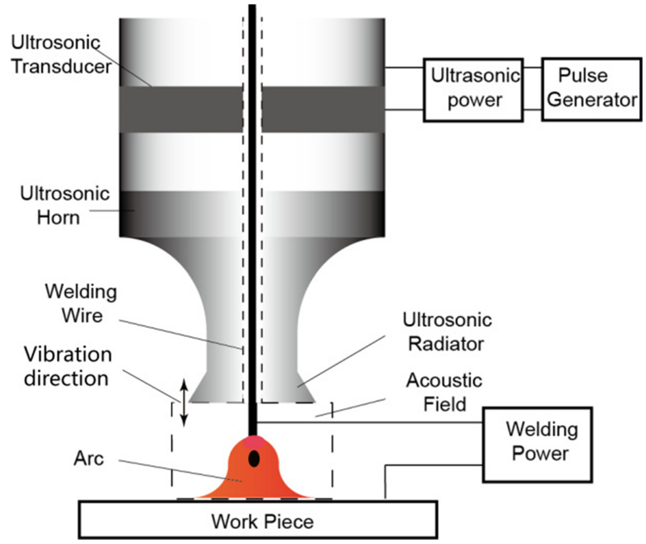

Fig. 2 Schematic of PU-GMAW system

coupled. Fan et al. [15, 16] found that under the action of URF, the volume of the droplet decreased and the transfer frequency increased obviously [9]. However, since the ultrasonic wave was continual, the URF and droplet transfer did not realize the goal of time matching, i.e., the loading time and magnitude of the URF were not controllable and optimal.

In this study, pulsed ultrasonic wave is employed to interfere the arc and control the droplet transfer, and the method been named as pulsed ultrasonic wave-assisted GMAW (PU-GMAW). During PU-GMAW, a periodic ultrasonic resonant field is built up in which the welding arc burns. The pulsed ultrasonic field will inevitably lead to periodic changing of URF. The magnitude and loading time of the pulsed URF can be regulated by changing the exciting current and pulse frequency of the ultrasonic wave. Thus, under the action of the pulsed ultrasound, the droplet transfer would be regulated more effectively.

2 Experimental procedure

The schematic of PU-GMAW system is shown in Fig. 2. The welding power source is Kemppi Pro MIG500, and the ultrasonic power source is CQF-1000. The frequency of the ultrasound is 20 ± 1KHz, and the pulse frequency of the ultrasonic power source is 0–20 Hz. 1060 aluminum plate with the thickness of 6 mm was used as the weldment, and S301 aluminum wire (ø1.2 mm) was selected as the welding wire. Since this study focused on the welding arc and droplet transfer, the overlay welding was adopted. Pure argon with the purity of 99.99% has been used as the shielding gas, and the flow rate was 25 L/min. A high-speed camera with 2000 FPS was used to obtain the arc shape and the droplet transition process.

As shown in Fig. 2, the ultrasonic wave has been radiated from the end of the radiator, and when it "hit" the surface of the reflector (the work piece), a reflected wave would generate. The ultrasonic wave and the reflected wave would "meet" in the arc space and led to an ultrasonic standing resonant field. This field is the main reason why the URF generated. Since the incident wave is in pulse form, the ultrasonic-standing resonant field and the URF varied at the same frequency. Since the arc burns in the ultrasonic standing resonant field, the pulsed URF would inevitably act on the arc and the droplets.

Based on the precious test, the best parameters of the ultrasonic field and welding are shown in Tables 1 and 2. What should be pointed out is that the radiator height in Table 1, which means the distance between the ultrasonic radiator end and the work piece.

3 Experimental results and analysis

3.1 Analysis of arc shape

Figure 3 shows the welding arc under different welding conditions. For all photos, the position of the camera is fixed.

It can be seen that the arc length is shortened obviously under the action of ultrasound, whether the ultrasound is pulse

Table 1 Parameter of the ultrasonic wave field

Ultrasonic frequency /KHz	Ultrasonic amplitude /μm	Radiator end diameter /mm	Radiator height /mm
20.1	30	28	29

Table 2 Welding parameters

Wire feed speed /m/min	Welding voltage /V	Pulsed frequency /Hz	Welding speed /m/min
8	25	0–15	0.4

or not. Compared with the U-GMAW arc, the arc length shrinks more greatly under pulsed ultrasound. Besides, the arc for conventional GMAW is typical bell-shaped, while after the application of ultrasound, the arc is changed into conical shape. Figure 4 shows the variation of the arc length with the pulsed ultrasound frequency. Compared with the conventional GMAW, the arc length with continuous ultrasound is shortened to 28.9%, and the arc length of 6 Hz pulsed ultrasound is further shortened to 46.7%. The arc length of conventional GMAW is longest, which means the arc is susceptible to the external environment and instability, and this has been observed in the experiment.

Since the arc is a flexible conductor, the motion of the particles inside determines the arc shape and length. Under the action of URF, the transverse motion of the particles is limited, while the axial motion is promoted [1]. Thus, the particle collision is intensified, which will increase the arc column electric field strength and arc temperature. The more prominent effect of the pulsed ultrasound mainly due to that the periodic URF can aggravate the particle collisions.

3.2 Analysis of the droplet shape and size

Figure 5 shows the globular transfer process of GMAW, U-GMAW, and PU-GMAW. Since the view field of the camera is exactly the same, the figures also indicate the effect of ultrasonic compression on the welding arc.

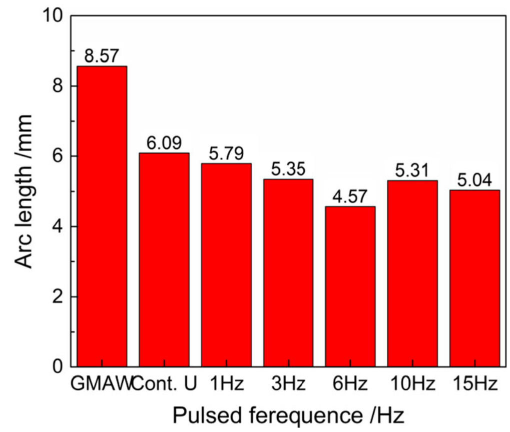

Fig. 4 Relation of the arc length and the pulsed ultrasound frequency

The droplet diameter is measured as shown in Fig. 5a. The droplet diameter of conventional GMAW is 1.83 mm, which is about 1.5 times of that of the wire, and the shape of the droplet is similar to an irregular ellipsoid, as shown in Fig. 5a. Under the action of continuous ultrasonic, the droplet diameter is reduced to 1.53 mm, but the droplet deformation has not been improved (Fig. 5b). Under the 6 Hz pulsed ultrasound, the droplet diameter is only 1.3 mm (Fig. 5e), which is roughly the same as the wire diameter and reduced to 29% of that of GMAW. Besides, under the pulsed ultrasound, all the droplets tend to appear spherical shape, regardless of the frequency of the ultrasound, which can be seen in Fig. 5c–f. Compared with the continuous ultrasonic action, the directivity of droplet transfer obviously improved under the action of pulsed ultrasound.

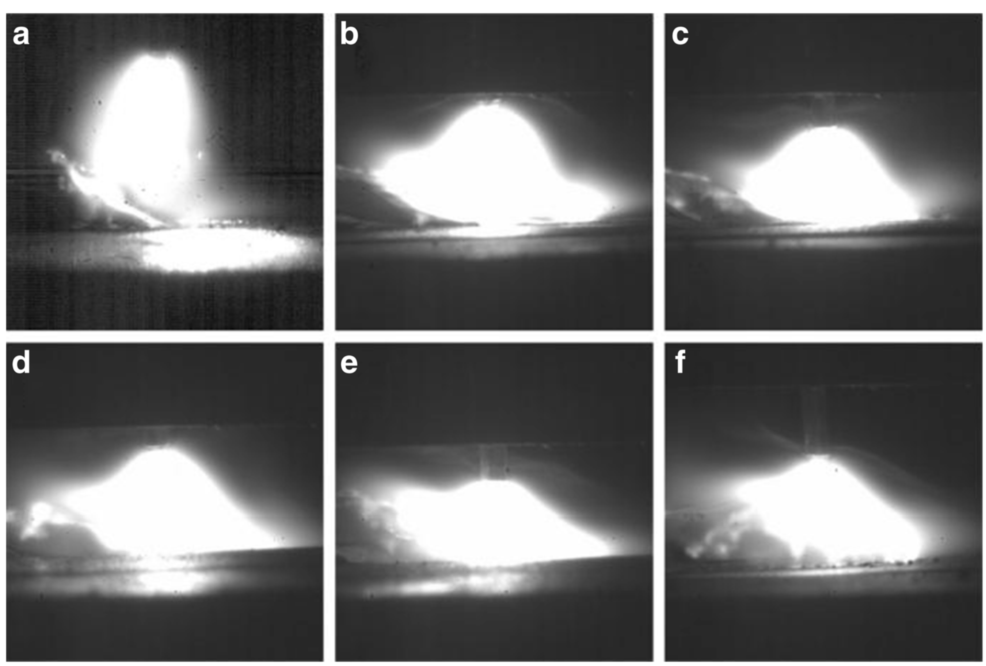

Fig. 3 Arc shape under the different ultrasonic parameters **a** conventional GMAW **b** continuous ultrasonic wave **c** 1 Hz pulsed ultrasound **d** 3 Hz pulsed ultrasound **e** 6 Hz pulsed ultrasound **f** 15 Hz pulsed ultrasound

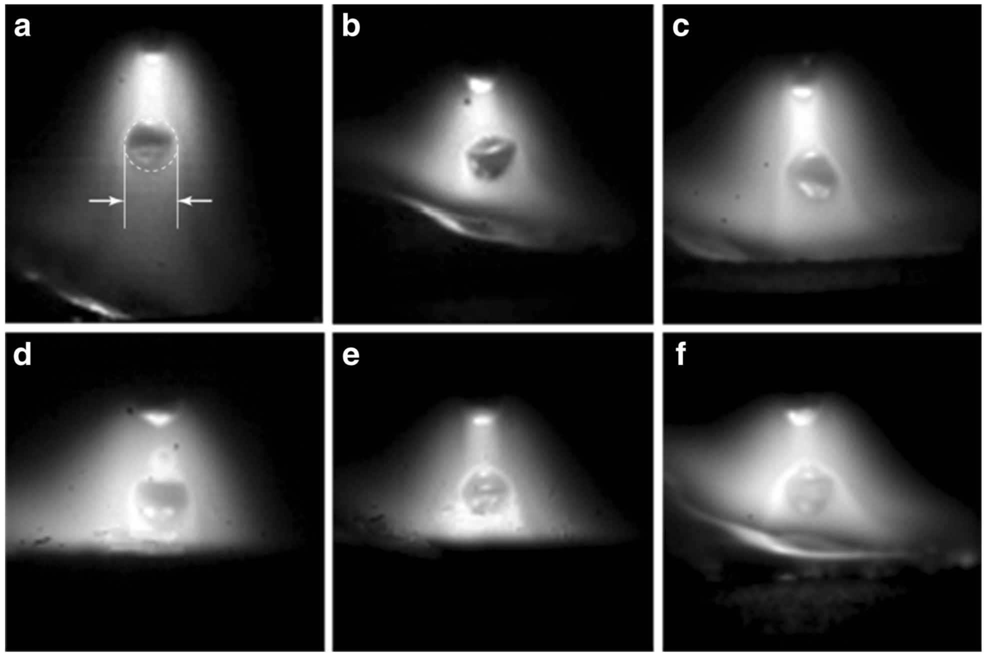

Fig. 5 Droplet shape under the different ultrasonic parameters **a** conventional GMAW **b** continuous ultrasonic wave **c** 1 Hz pulsed ultrasound **d** 3 Hz pulsed ultrasound **e** 6 Hz pulsed ultrasound **f** 15 Hz pulsed ultrasound

The underlying reasons of the ultrasound effect on the droplets are complicated. On the one hand, the droplet is compelled to fall off from the wire end before it growing up under the extra detaching force-URF (as shown in Fig. 1). With the amount of detaching droplets per unit time increases, the volume of per droplet of course decreases. On the other hand, unlike the continual ultrasonic mode, in the intermittent period of the pulsed URF, the surface tension will cause the droplets to concentrate to spherical shape.

3.3 Analysis of droplet transition frequency

Figures 6, 7, and 8 show the typical droplet transfer process of conventional GMAW, U-GMAW, and PU-GMAW individually.

As can be seen from Fig. 6, the droplet transfer period of conventional GMAW is 7 ms, and the transition frequency is 143 Hz. Under the action of continuous ultrasonic wave, the droplet transfer period is reduced to

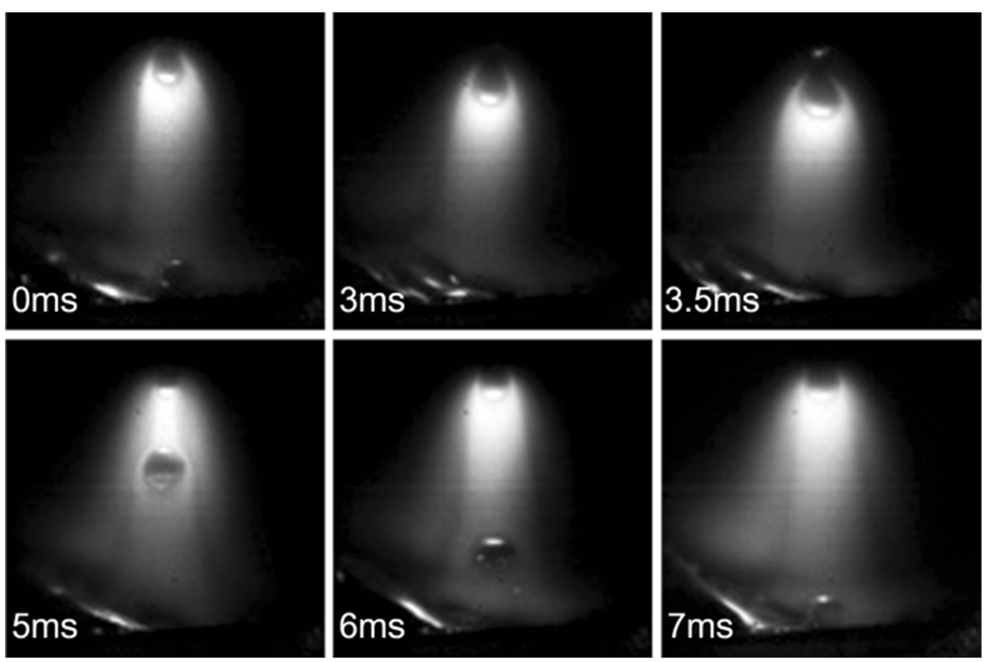

Fig. 6 The cycle of droplet transfer of conventional GMAW

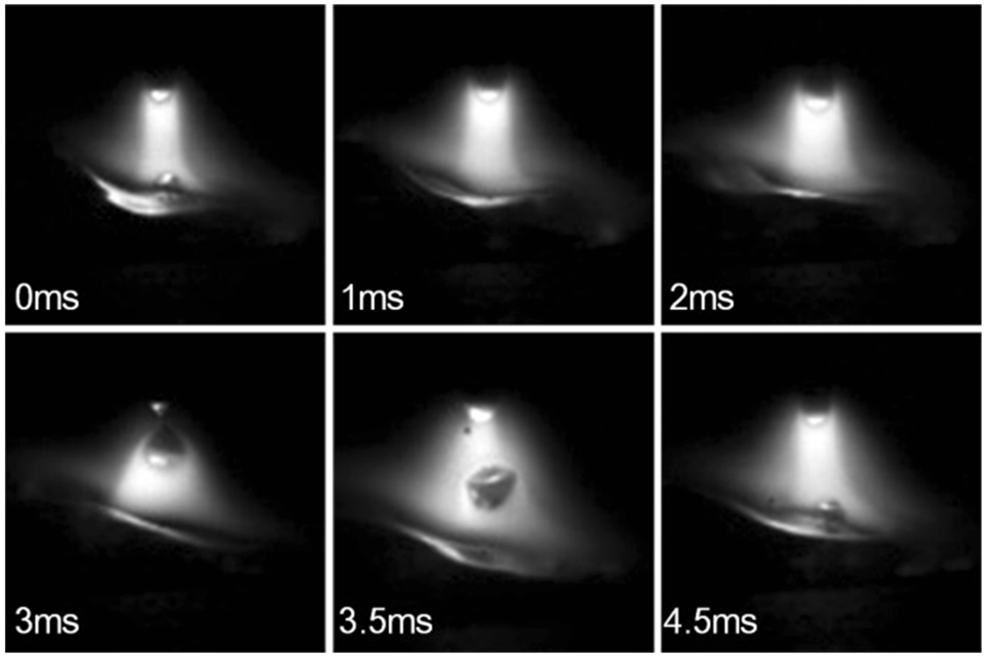

Fig. 7 The cycle of droplet transfer of U-GMAW

4.5 ms; as shown in Fig. 7, the transition frequency increases to 222 Hz. Compared with conventional GMAW, the U-GMAW arc is obviously compressed and the arc brightness increased. Figure 8 shows that under the pulsed ultrasound with 6 Hz frequency, the droplet transfer period decreased to 3.5 ms and the droplet transition frequency reaches 285 Hz. Under the pulsed ultrasound, the arc brightness, which can be regarded as a symbol of the arc energy density, is significantly improved, and this is conducive to the improvement of the weld penetration.

The droplet transition frequency at different pulse frequencies is plotted as a histogram in Fig. 9. It can be calculated from the figure, under the 6 Hz pulse ultrasound, the droplet transition frequency is almost 2.8 times than that of conventional GMAW and 1.28 times than that of U-GMAW.

Figure 10 shows the pulsed input current acted on the ultrasonic transducer; it is clear that the signal is not an ideal square wave. At the peak stage, the current is high and even, but at the base stage, the current gradually decreases. The

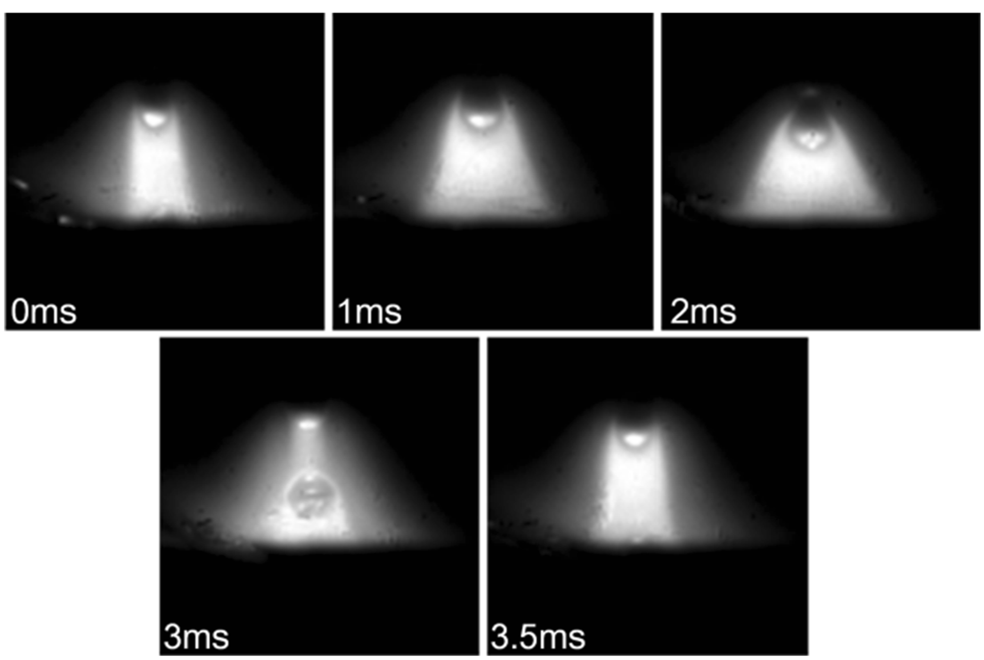

Fig. 8 The cycle of droplet transfer of 6 Hz PU-GMAW

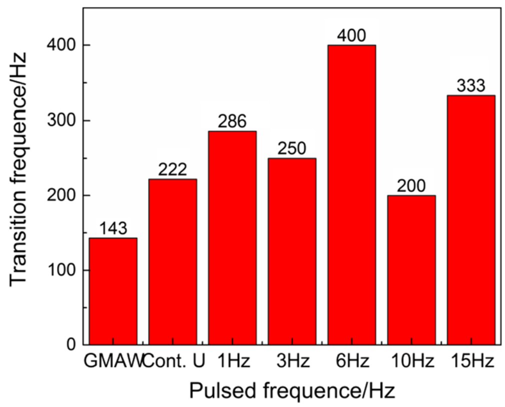

Fig. 9 The frequency of droplet transfer

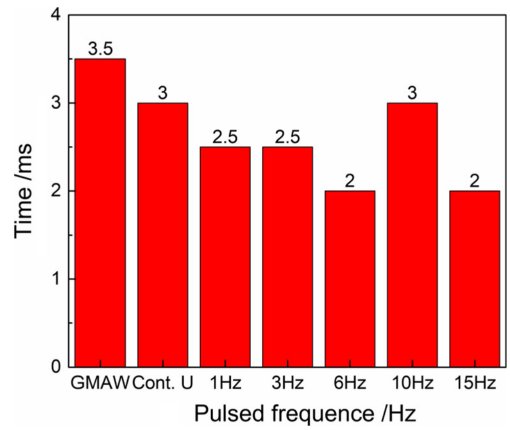

Fig. 11 The situation of droplet transfer

variation of the current indicates the variation of the ultrasonic wave amplitude (or URF) at the meanwhile. This strong-damping-zero mode of ultrasonic wave is the fundamental reason why pulsed ultrasound can promote the droplet transfer more effectively than continuous ultrasound.

3.4 Analysis the movement process of the droplet

The droplet transfer process can be divided into two stages. In the first stage, the droplet forms and grows at the end of the wire, and in the second stage, the droplet flies towards the molten pool. The time of the first stage also determines the size of the droplet, and the time of the second stage depends mainly on the velocity of droplet movement and the distance/arc length.

The residence time of the droplets at the end of the wire under different pulse ultrasound frequencies are shown in Fig. 11. It is obvious that under 6 and 15 Hz, the residence time is greatly reduced, which is consistent with Fig. 9. It is puzzling that, although 10 Hz is between 6 and 15 Hz, the effects on droplet growth and transition are quite different, as shown in Figs. 9 and 11, and the same phenomenon appeared at the 3 Hz similarly.

The relationship between the displacement and time of the droplets under some typical welding conditions is shown in Fig. 12. It seems that all the droplet movement conforms to a linear function. The slope of the fitted line in Fig. 12 represents the velocity of the droplet. The speed of the conventional GMAW droplet is calculated as 1.74 m/s, and for U-GMAW, the droplet speed increases to 1.93 m/s. Under the action of pulsed ultrasound, the velocity of the droplet is obviously increased. When the pulse frequency is 6 Hz, the droplet velocity reaches 2.17 m/s, which is approximately equal to that of 15 Hz. However, under the 15 Hz, the arc length and transfer period are longer, generally 6 Hz is the best.

4 Influence of the ultrasound on the weld formation

The overlay welding appearance of conventional GMAW, U-GMAW, and PU-GMAW of 6 Hz is shown in Fig. 13. It is found that the weld width increases obviously after applying ultrasound or pulsed ultrasound, while the oxidation degree of weld appearance decreases. In addition, the splash of the welding process is reduced and the forming quality is

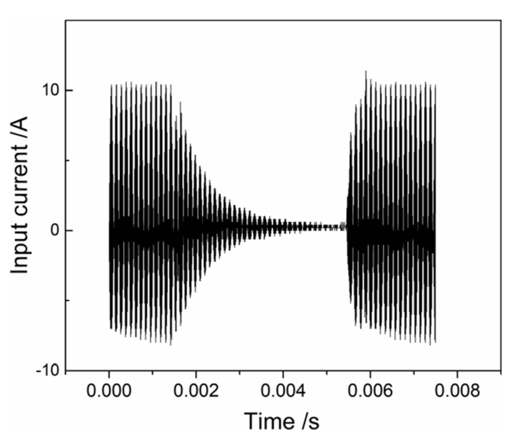

Fig. 10 The input current of the ultrasonic transducer

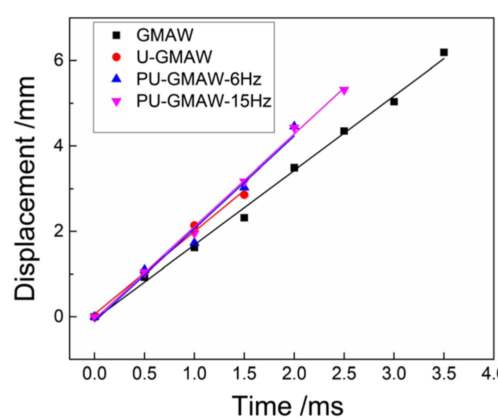

Fig. 12 Fitting line of displacement-time relationship

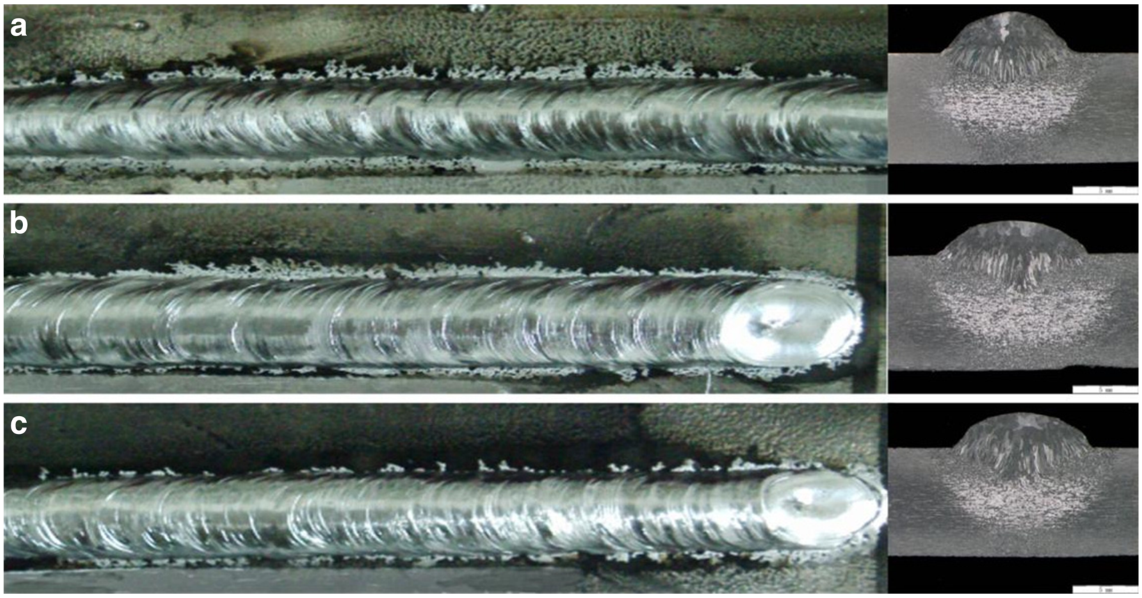

Fig. 13 Weld appearance and bead formation **a** conventional GMAW **b** U-GMAW **c** 6 Hz pulsed ultrasound

improved. The shape parameters of the weld are shown in Table 3.

It is clear that the weld penetration and width increase both after the ultrasonic is applied. Since the increase degree of the penetration is much higher, the aspect ratio increases. Compared with GMAW, under the 6 Hz pulse frequency ultrasound, the aspect ratio increases from 0.19 to 0.27, and the increase rate is up to 37%. This is because under the pulsed ultrasound, the axial direction of arc is contracted and the molten pool flows more violently, and the heat (or energy) is transmitted more readily to the deeper part of the weld. The radial length of arc also increases resulting in the weld width increase, while the growth rate is smaller, as illustrated in Fig. 14.

5 Conclusions

(1) The arc of conventional GMAW is bell-shape. Under the action of pulsed ultrasound, the arc was compressed to the conical shape and the length shortened obviously. The shorten rate of the arc length under 6 Hz pulsed ultrasound is up to 46.7%.

Table 3 The characterization parameters of welding seam

UltrasonicUltrasonic parameters	Weld penetration /mm	Weld width /mm	aspect ratio	Reinforcement /mm
GMAW	2.09	10.53	0.198	3.20
U-GMAW	2.95	11.69	0.252	2.59
6 Hz	2.92	10.78	0.271	2.70

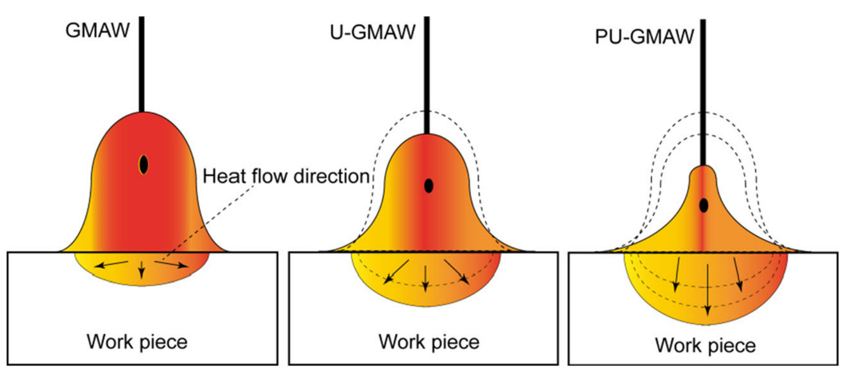

Fig. 14 The change of arc shape and molten pool

(2) Under the 6 Hz pulsed ultrasound, the diameter of the droplet decreases from 1.83 mm of conventional GMAW to 1.3 mm. The reduce proportion of the droplet diameter is as high as 29%. Simultaneously, the transition frequency reaches 285 Hz, which is almost two times than that of conventional GMAW.
(3) The application of ultrasound increases the aspect ratio of the welding seam. The aspect ratio of the welding seam with 6 Hz pulsed ultrasound is the highest, reaching 0.27. It is because under the action of the ultrasound, the arc energy density increases, and the heat is easier conduct to the deeper part of the molten pool.

6 Research prospect

From the results, it seems that the influence of the ultrasonic frequency on the arc shape and droplet transfer is not linear, some specific frequencies have more obvious effect; the intrinsic mechanism needs to be studied deeply.

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References

1. Kim YS, Eager TW (1993) Analysis of metal transfer in gas metal arc welding. Weld J 72:1143–1152
2. Liao MT, Chen WJ (1999) A comparison of gas metal arc welding with flux-cored wires and solid wires using shielding gas. Int J Adv Manuf Technol 15(1):49–53. https://doi.org/10.1007/s001700050038
3. Xie WF, Fan CL, Yang CL, Lin SB (2016) Effect of acoustic field parameters on arc acoustic binding during ultrasonic wave-assisted arc welding. Ultrason Sonochem 29:476–484. https://doi.org/10.1016/j.ultsonch.2015.11.001
4. Anon (1976) Classification of metal transfer. IIW Document XII: 636
5. Tipi ARD, Sani SKH, Pariz N (2015) Improving the dynamic metal transfer model of gas metal arc welding process. Int J Adv Manuf Technol 76(1–4):657–668. https://doi.org/10.1007/s00170-014-6307-4
6. Simpson SW (2009) Metal transfer instability in gas metal arc welding. Sci Technol Weld Join 14(4):262–273. https://doi.org/10.1179/136217109X406901
7. Haidar J (1999) An analysis of the formation of metal droplets in arc welding. J Phys D Appl Phys 31(10):1233
8. Gao Z, Jiang P, Wang C, Wang C, Shao X, Pang S, Zhou Q, Li X, Wang Y (2016) Study on droplet transfer and weld quality in laser-MIG hybrid welding of 316L stainless steel. Int J Adv Manuf Technol 88(1–4):1–11
9. Campana G, Fortunato A, Ascari A, Tani G, Tomesani L (2007) The influence of arc transfer mode in hybrid laser-mig welding. J Mater Process Technol 191(1):111–113. https://doi.org/10.1016/j.jmatprotec.2007.03.001
10. Huang Y, Zhang YM (2010) Laser-enhanced GMAW. Weld J 89(9):22–27
11. Kang YH, Na SJ (2003) Characteristics of welding and arc signal in narrow groove gas metal arc welding using electromagnetic arc oscillation. Weld J 82(5):93s–99s
12. Zhang X, Zhao Z, Mi G, Wang C, Li R (2017) Effect of external longitudinal magnetic field on arc plasma characteristics and droplet transfer during laser-MIG hybrid welding. Int J Adv Manuf Technol 13:1–11
13. Pickin CG, Young K (2006) Evaluation of cold metal transfer (cmt) process for welding aluminium alloy. Sci Technol Weld Join 11(5):583–585. https://doi.org/10.1179/174329306X120886
14. Fan YY, Yang CL, Lin SB, Liu WG (2012) Ultrasonic wave assisted GMAW. Weld J 91(3):91s–99s
15. Fan CL, Xie WF, Yang CL, Kou Y (2014) Characteristics of welding arc during ultrasound-MIG hybrid welding of aluminum alloy. Trans China Weld Inst 35(001):5–8
16. Fan CL, Yang CL, Lin SB, Fan YY (2013) Arc characteristics of ultrasonic wave-assisted GMAW. Weld J 92(6):375s–380s