The International Journal of Advanced Manufacturing Technology (2018) 98:2895–2904
https://doi.org/10.1007/s00170-018-2438-3

ORIGINAL ARTICLE

Research on arc cutting mechanism and procedure of flux-cored cutting wire in water

Wenhang Li [1] · Jingyu Zhao [1] · Jiayou Wang [1] · Jianxin Wang [1] · Haifeng Jia [1] · Zexin Li [1] · Sergii Yuri Maksimov [2]

Received: 21 December 2017 / Accepted: 16 July 2018 / Published online: 26 July 2018

Abstract
As an efficient underwater cutting method, flux-cored arc cutting's mechanism is not well studied because it is hard to directly observe the process. To reduce the interference from water, air cutting process was studied at first. We studied the impact of parameters on the cutting process by capturing cutting workpiece's edge images with a high-speed camera. The results showed that the arc moved up and down and meanwhile it moved with the torch in cutting direction. Secondly, a sandwich structure was designed to observe the underwater cutting process. The characteristics of air and underwater cutting were analyzed and compared. It was found that underwater cutting process was similar to that in air. Thirdly, a pressure vessel device was used to simulate conditions at different water depths up to 100 m, and the influence of main characteristics was analyzed according to the cutting mechanism. As water pressure increases, the kerf shape becomes narrower, melting speed of cutting wire accelerates, and the stability of the arc gets worse in deep water. The relative research on cutting mechanism and process is significant to further cutting automation and engineering applications.

Keywords Flux-cored cutting wire · Underwater cutting · Cutting mechanism · Cutting procedure

1 Introduction

The underwater cutting technology has been widely applied in many industries, such as marine construction, nuclear reactor demolition, underwater repair of ship building, and underwater salvage [1–3]. The flux-cored arc cutting method [4], developed by Ukraine Paton Electric Welding Institute, is widely used in underwater metal arc cutting due to its advantages of low cost, simple equipment, and high efficiency. The arc ignited between the flux-cored wire and the workpiece, heated to melt the metal, and the gas produced by the flux-cored wire blew off the molten metal. Since the mechanism and process of underwater flux-cored arc cutting are still not clear, we studied this process in this paper so as to further improve its efficiency, stability, and automation level.

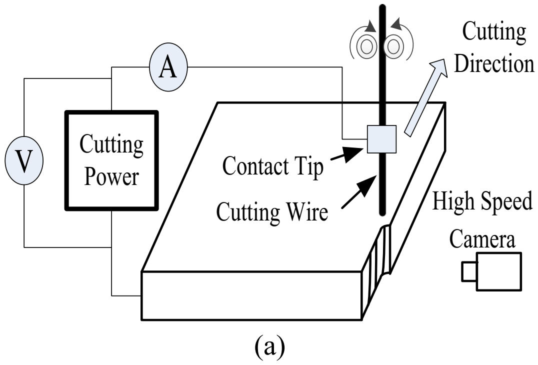
✉ Wenhang Li
lwh_abc@qq.com

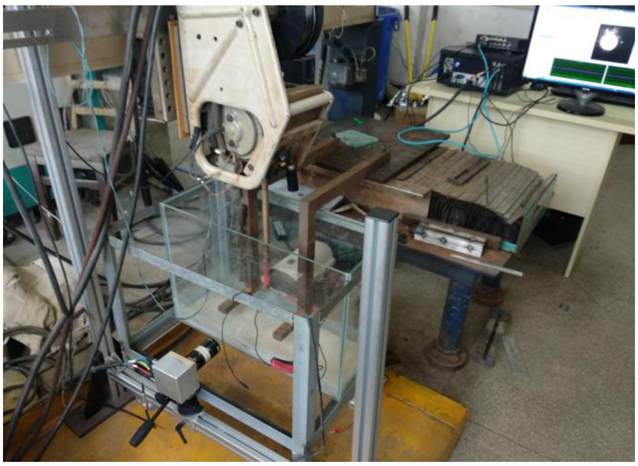
[1] School of Materials Science and Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, Jiangsu Province, People's Republic of China

[2] E.O.Paton Electric Welding Institute, Kiev 03680, Ukraine

Flux-cored cutting wire was first applied to underwater wet cutting by M E Danchenko and Yu N Nefedov et al. [5, 6], who created three types of flux-cored wire and developed the semi-automatic underwater cutting technology. The effects of wire's chemical composition and underwater arc combustion stability were studied; however, the cutting mechanism and cutting process were not studied in this paper. Yu YA Gretskii et al. [7] studied the peculiarities of underwater flux-cored wire arc cutting without additional supply of oxygen. The mechanism of underwater cutting process was studied indirectly through statistical analysis of characteristic parameters such as cutting electrical parameters, kerf shape, etc. with arc burning alternately in two spaces ("cutting wire tip–molten metal", "cutting wire lateral surface–kerf edge"). This study only established the concept of the cutting mechanism, and the results were not sufficient to explain the underwater cutting arc phenomenon because the cutting arc was not observed directly.

In other underwater cutting-related fields, Masanobu et al. [8, 9] conducted extensive researches on underwater arc cutting with high-pressure water jet technique. They used high-speed cameras to capture arc images and concluded that the arc was generated by repeated contact of the wire with the workpiece. Yu et al. [10] found some characteristics





(b)

Fig. 1 Located at the edge of the workpiece cutting method. **a** Schematic diagram. **b** The real setup

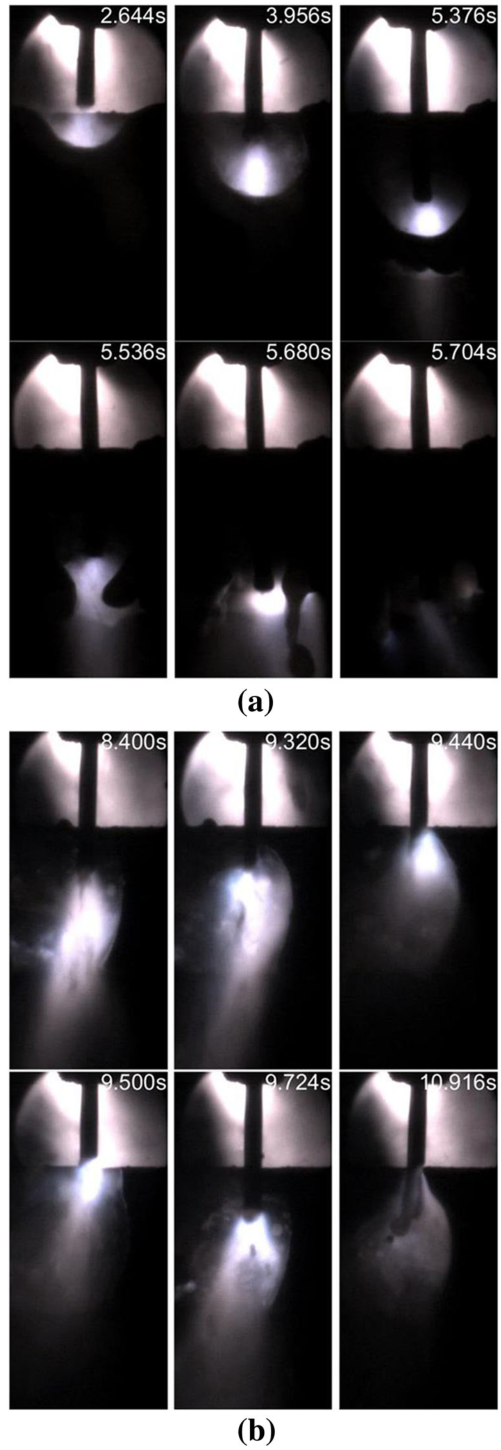


Fig. 2 Cutting process in air. **a** Arc extinguish after reaching the bottom of the workpiece. **b** Arc strike after cutting wire touching the top of the workpiece

of the melting cut wire and proposed two cutting modes in the study of underwater arc cutting with water jet. Wu et al. [11] discussed the cutting phenomena at four cutting speeds. Yoji studied the thin wall stainless steel underwater cutting and Haferkamp completed the climbing robot for underwater cutting [12, 13]. The water jet arc cutting mode has been experimented and production application has begun to be developed, but the arc cutting mechanism was yet to be studied. Moreover, the water jet cutting and flux-cored arc cutting are different in the following four aspects: (1) water spray will affect the movement of the arc; (2) the wire is solid; (3) the electrode shape between the workpiece and the cut wire looks like a band; (4) wire feed speed has no effect on the current. In addition, Tian et al. [14] investigated electric arc cutting process for casing and studied its effect in different working medium, and concluded that electrical arc can cut in seawater. This method is different from flux-cored arc cutting, which involves a tungsten electrode. But, the cutting mechanism was not studied.

A joint study in cooperation between Jiangsu University of Science and Technology and the Ukrainian Paton Electric Welding Institute is conducted recently to build flux-cored wire underwater cutting system. Wang et al. [15, 16] studied the factors of kerf forming in lower water depth. However, the decomposition of the flux-cored cut wire's component caused a large amount of opaque bubbles to jump around the arc, which makes it difficult to directly observe the underwater cutting arc.

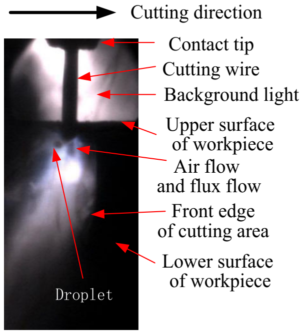


Fig. 3 Droplet transfer mode of cutting process

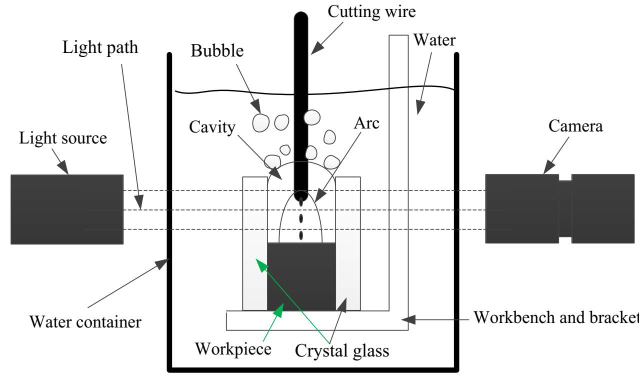


Fig. 5 Schematic diagram of observing device for underwater cutting

Moreover, because the cutting wire usually extends to the interior of the workpiece, it is difficult to observe the cutting process even with X-ray inspection [17]. Therefore, it is necessary to find ways to overcome these adverse effects.

In this paper, new observation methods were proposed to clarify the underwater flux-cored arc cutting mechanism. Firstly, cutting experiments in air can avoid the influence of the water environment, and the workpiece was cut at its edge to avoid the negative influence on observation when the cutting wire extended into the workpiece. Secondly, a sandwich structure was designed to reduce the influence of water fluctuation and opaque bubble and with a high-speed camera to observe the underwater cutting process. We then tried to prove that the in-air cutting is similar to the underwater one. The cutting procedure was done and analyzed according to the cutting mechanism.

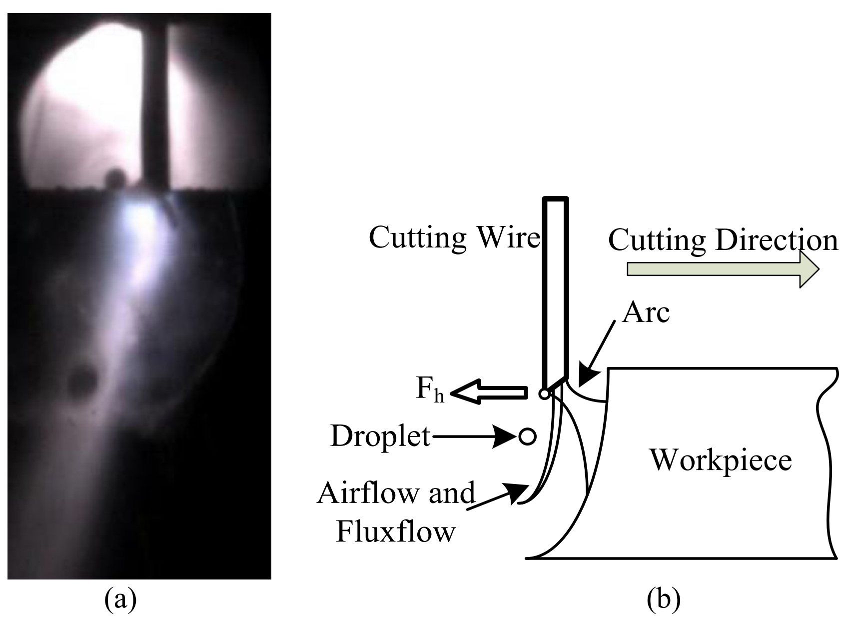
The rest of the paper is organized as follows. In section 2, the flux-cored arc cutting mechanism in air and underwater was analyzed, and a typical cutting mode was proposed. In section 3, the influence of cutting procedure parameter was studied, and the cutting experimental results and the cutting mechanism were verified. Section 4 concludes this paper and provides future prospects.

2 Analysis of cutting mechanism

2.1 Cutting mechanism in air

As mentioned above, we first cut the workpiece in air to avoid the influence of water. In addition, the workpiece was cut at its edge to avoid the negative influence on observation when the cutting wire extended into the workpiece. As illustrated in schematic Fig. 1a, an “arc sensor–high speed photography” synchronous acquisition system was set up to obtain cutting current, arc voltage, and images of cutting area.

Fig. 4 Droplet transfer of cutting process with hangover. **a** Physical map. **b** Schematic diagram



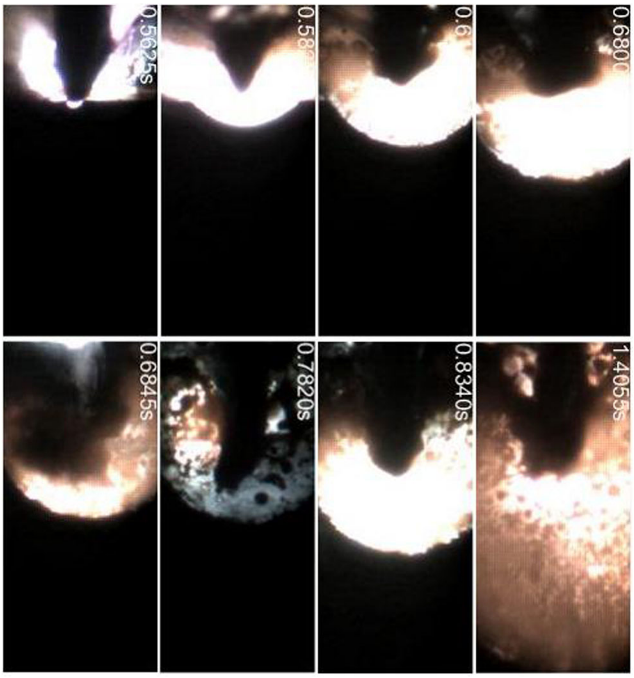


Fig. 6 Image of underwater cutting process

The cutting equipment is as follows: the cutting power source was Panasonic KR500, which was operated with a constant wire feed speed and in DC constant-voltage mode. The base metal prepared for this experiment was Q235 mild steel with dimensions of 300 mm × 150 mm × 16 mm. The self-shielded PPR-AN2 flux-cored wire with a diameter of 2.0 mm was made in Paton Electric Welding Institute of Ukraine. The real setup is showed in Fig. 1b. The transparent glass case is used for underwater cutting when the water depth is 0.2 m, but not used for cutting in air in case of damaging.

The underwater cutting equipment was similar to that of the flux-cored wet welding, except that the shielding gas was from external supply. By changing the cutting speed, arc voltage, and cutting current (by changing the wire feed speed), the cutting process and droplet transfer were analyzed.

Figure 2 shows two typical phenomena in cutting process with two different cutting speeds. As shown in Fig. 2a, the arc continuously heated and melted the metal below during the starting stage, and the gas flow generated by the flux expelled the molten metal. With the removal of metal, the arc first became longer, and then got shortened due to arc self-regulation. Therefore, the wire would extend into the workpiece. When the metal below the arc was totally removed, a hole was formed. As shown in Fig. 2a, if the cutting speed was relatively low, the wire end would go through the workpiece and the arc would extinguish when the arc was too long and the arc disappeared for a while.

Until the cutting wire moved forward and re-contacted with the upper part of the workpiece, the arc re-struck very quickly and moved to the top of the workpiece and repeated the same process.

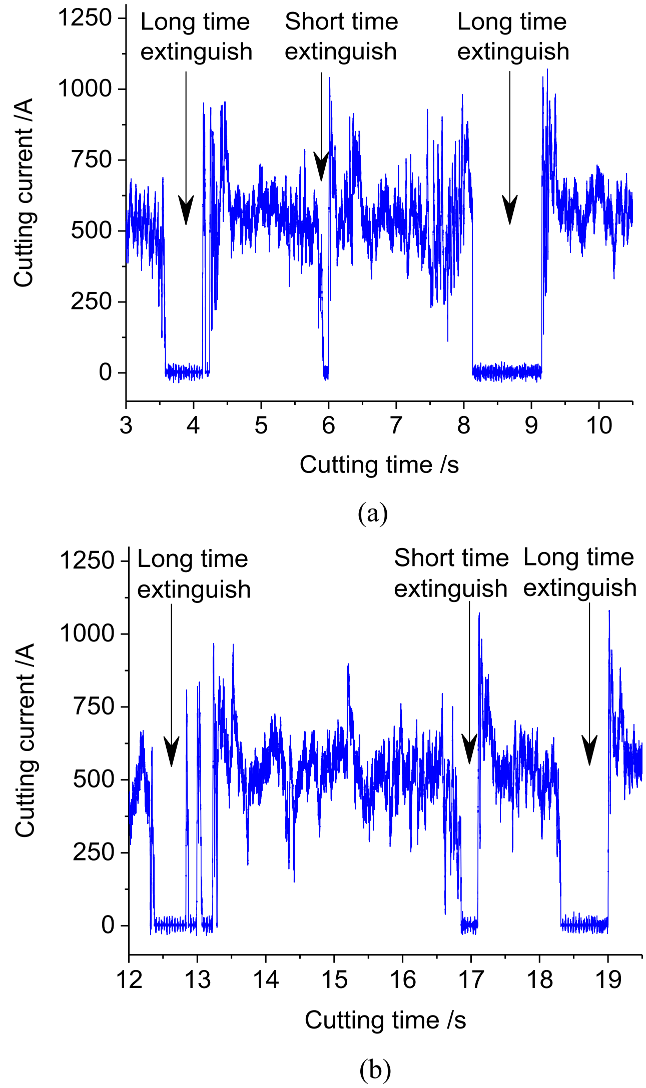


Fig. 7 Current waveforms of cutting process. **a** In air. **b** Under water

As shown in Fig. 2b, if the cutting speed was faster, the wire would contact with the workpiece in the cutting direction before the wire moved through the workpiece and the arc ignited at the top of the workpiece. In this case, the arc stayed at the middle and upper part of the workpiece in thickness direction. In general, the arc moved forward and up and down periodically, made the cut hole into a long cut gradually.

Droplet transfer of cutting process is shown in Fig. 3. The cutting wire end was melted by arc heat, and the drop was likely to be expelled by the flow of gas and slag, which was produced by the reaction in flux. The droplet transfer process was mainly a fine particle metal transfer and the flow direction was basically coaxial with the cutting wire, because flow was not conductive. Although most of the cutting wire presented free transfer, a short circuit easily occurred at the front edge of

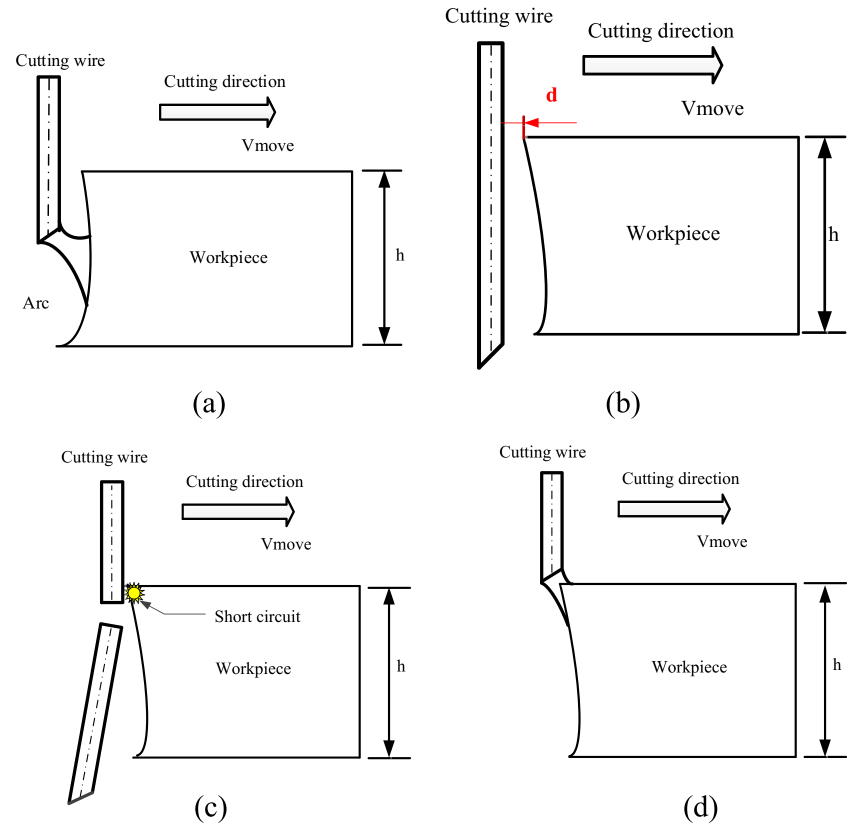


Fig. 8 A typical arc cutting mode. **a** The arc is burning inside the workpiece. **b** The tip of wire is too long from the bottom of the workpiece; at this time, the arc extinguishes. **c** A short circuit occurs between the side of wire and the front of the workpiece. **d** The arc ignites again

the cut with cutting wire moving forward. If the arc ignited successfully, and the arc would shift here.

When the arc's average vertical position was relatively high, the lower workpiece got less heat and a slope formed because of inhomogeneous heat distribution so that the droplet tended to transfer to kerf's rear area at this moment, as shown in Fig. 4a. Figure 4b shows its schematic diagram where the arc direction pointed to the front of the kerf in the cutting process according to the principle of minimum voltage. Then, electromagnetic force and spot pressure had a horizontal component Fh which was opposite to the cutting direction so that the droplet tended to transfer backward.

2.2 Cutting mechanism in water

It is difficult to observe the cutting arc directly due to the presence of water fluctuation and opaque bubbles as a result of reaction product of flux-cored cutting wire decomposed in water. Therefore, a sandwich structure was designed to reduce these adverse influences and observe the process of underwater cutting. As shown in Fig. 5, the structure was placed in transparent water tank where two crystal glass pieces were adhered on both sides of a workpiece, and the workpiece width was designed as 6 mm so that the workpiece can be completely melted in the workpiece width direction. Accordingly, the background light source can pass through the workpiece to camera.

Figure 6 is the captured picture of the cutting process. When the water depth was 0.2 m, cutting current was 500 A with the corresponding wire feeding speed being 5.5 m/min and cutting voltage being 40 V. The underwater arc also continuously heated and melted the metal, and expelled the molten metal with the gas generated by the flux. Subsequently, the arc continued to decline in the role of the self-regulation system, then a hole was formed in the workpiece thickness direction from top to bottom.

On the other hand, Fig. 7 is the current waveforms with the same parameter in air and in water, respectively. The trend of both waveforms was similar, concluding of three stages of arc burning, short time distinguish, and longtime distinguish in cutting process.

The images and current waveforms of cutting process were compared and analyzed to show that underwater cutting mechanism was similar to that in the air.

2.3 Proposing a typical cutting mode

As mentioned above, according to the flux-cored arc cutting mechanism, a typical cutting mode was proposed. The cutting process can be divided into four stages in one cutting period. In Fig. 8a, the arc is

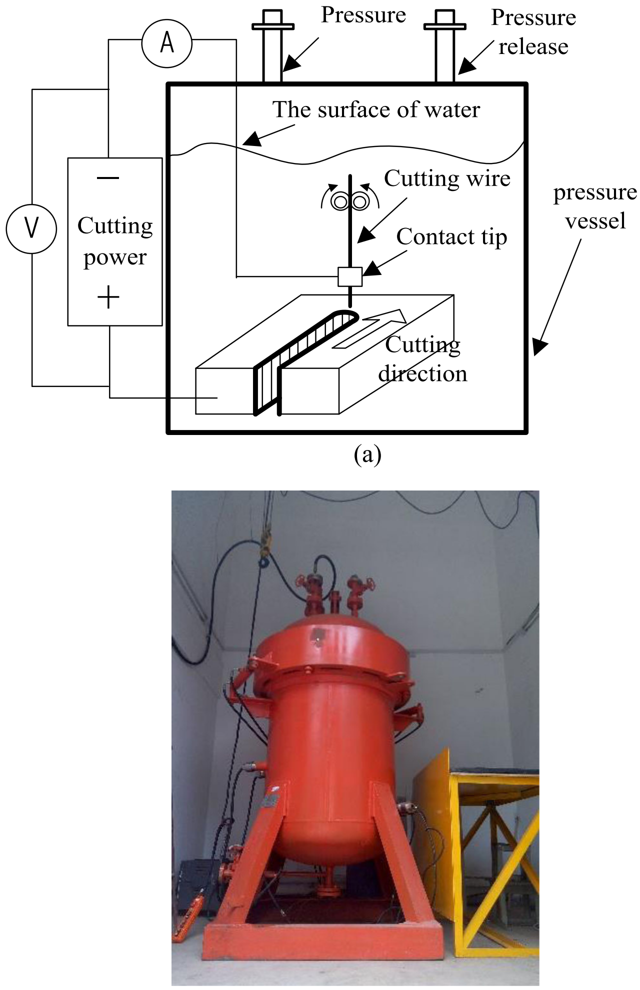


Fig. 9 Underwater cutting experiment system. **a** Underwater cutting diagram. **b** pressure vessel physical map

burning inside the workpiece. When the arc melted and metal was removed, the wire end went through the workpiece and the arc extinguished immediately, as shown in Fig. 8b. At this moment, the distance between the side of wire and the front of the workpiece is d. In this process, the arc burning time is t1 from the upper surface to bottom of the workpiece, and a long time extinguish time is t2, which can be expressed by eq. 1 and eq. 2, respectively. As cutting process continued, the side of wire contacted with the workpiece in the cutting direction and there appeared a short circuit, resulting in the melt of wire below the surface of the workpiece, as shown in Fig. 8c. Then, the arc ignites again at the top of the workpiece in Fig. 8d.

$$t_1 = {}^{h}/_{\mathrm{Vf}} \tag{1}$$

$$t_2 = {}^{d}/_{\mathrm{Vm}} \tag{2}$$

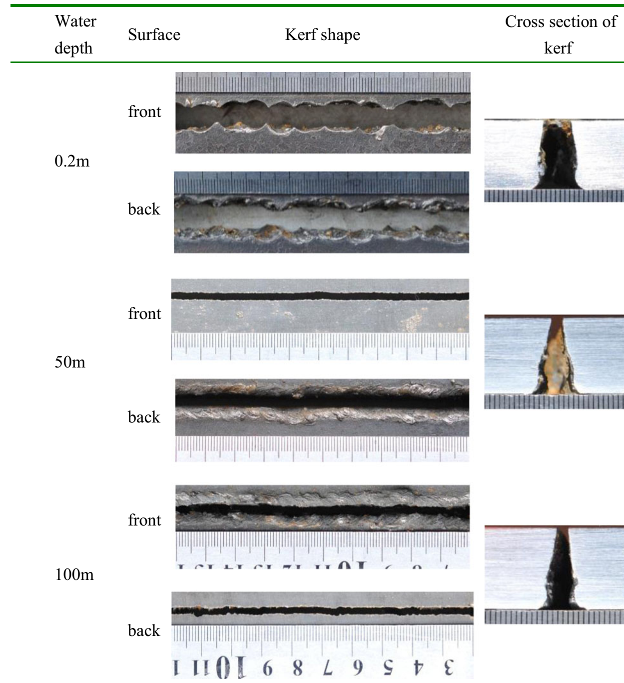


Fig. 10 The kerf shape in different water depths

h, the thickness of the workpiece; Vf, the decline speed of wire; Vm, the movement speed of cutting direction; *d*, the distance between the side of cutting wire and the top of the workpiece.

3 The influence of cutting process parameter

The underwater cutting system is shown in Fig. 9. The cutting system was placed in a pressure vessel, which can adjust different pressures to simulate the water pressure.

As mentioned in section 2, the process parameters were constrained in a narrow range because the main cutting parameter needed to cooperate. In addition, the range of the cutting process parameter varied with different water depths. In order to compare the influence of various parameters, only one parameter was changed at a time. The depth of water, the

Fig. 11 The average length of broken wire under different water depths

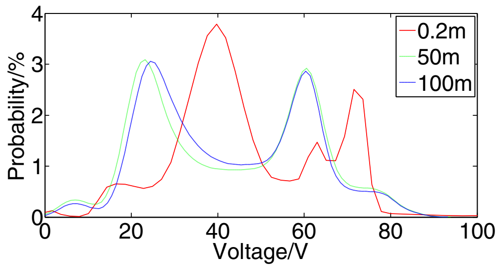


Fig. 12 Probability density distribution of voltage under different water depths

cutting current (adjusted by changing wire feed speed, which was in the ± 50 A range), and arc voltage (which was changed in the ± 5 V range) were changed in the experiment.

3.1 The influence of water depth on cutting process

The water depth or water pressure affects the arc shape and stability. To study its influence, the water pressure was adjusted to the water depth of 0.2, 50, and 100 m, respectively. The cutting current was 450 A, the corresponding wire feeding speed was 5 m/min, the cutting voltage was 40 V, and the cutting speed was 130 mm/min. The kerf shape is shown in Fig. 10.

Figure 10 showed that the kerf became much narrower when the water depth was larger than 50 m. The reason is that the arc was compressed with the increase of water depth. In addition, with the narrowing of the arc, the arc current density became large and the voltage stresses increased to ensure the current. Therefore, when the voltage was the same, the arc length would decrease with the increase of water depth. According to the underwater arc cutting mechanism, the arc average position decreased, resulting in its kerf shape changing from "| |"-type kerf to "∧"-type kerf. Moreover, Fig. 10 showed that the width of upper kerf is nearly the same wide as the diameter of cutting wire. Because there was a short circuit between the cutting wire and the workpiece, the heat from the lower part contributed to the formation of the upper kerf.

Moreover, it is found that the average length of broken wire became much shorter, as shown in Fig. 11, because the arc was compressed more and more severely with the deepening of water, and the arc current density became lager, causing melting speed of cutting wire to increase.

Furthermore, it is also found that the probability density distribution of voltage changed, as is shown in Fig. 12. It showed that the voltage was mainly distributed around 25 and 60 V when the water depth was larger than 50 m, showing that the instantaneous short circuit increased and the arc stability decreased.

3.2 The influence of cutting current on cutting process

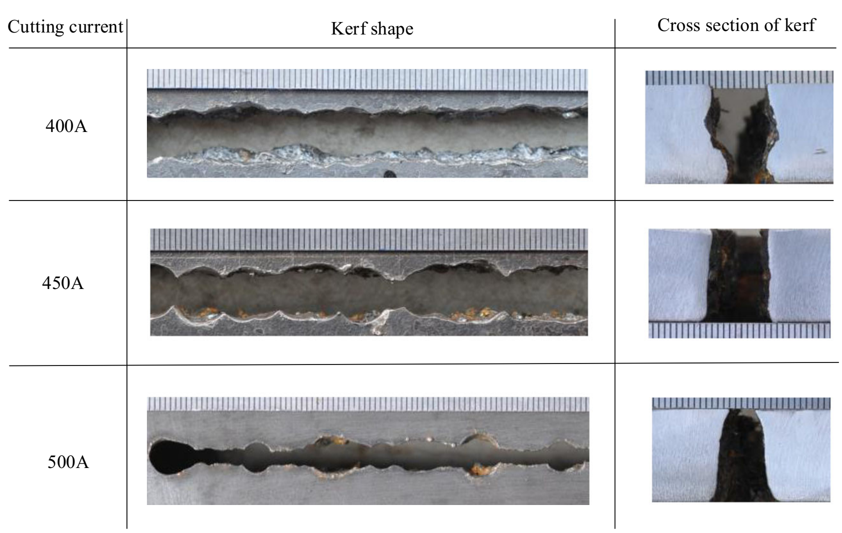
The cutting current affects the heat input in cutting process, as a result, the stability of the cutting process and the formation of kerf are affected. To study its influence, cutting current was set to 400, 450, and 500 A, respectively.

Firstly, the water pressure was adjusted to the water depth of 0.2 m. The cutting voltage was 40 V, and the cutting speed was 130 mm/min. The kerf shape is shown in Fig. 13.

As can be seen from the front of kerf, the circular ripple gradually occurs with the raising of cutting current. The reason is that higher current value increases the arc cutting ability, and decrease the time of wire from top to bottom, thus leading to the violent fluctuation of kerf width.

As can be seen from the cross section of kerf, the kerf shape changed from "∨" type to "| |" type and then "∧" type gradually with the raising of the cutting current. The upper kerf width gradually narrowed and the lower kerf width gradually widened. According to the underwater arc cutting mechanism, when the current was low, the arc mainly concentrated on the

Fig. 13 The kerf shape in different cutting current at the depth of 0.2 m



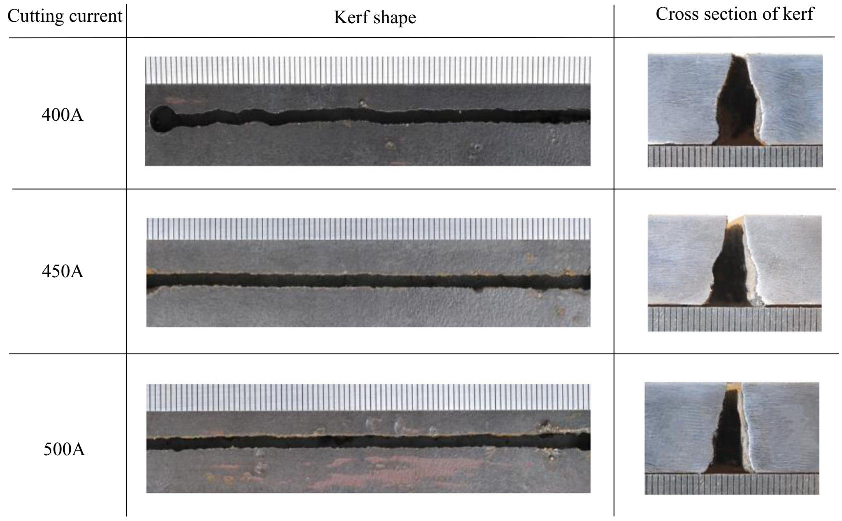


Fig. 14 The kerf shape in different cutting current at the depth of 50 m

upper part of the workpiece. In this way, the upper kerf was easily melted, forming the wide upper kerf. Besides, when the current was larger, the arc easily extended into the workpiece, there was a short circuit between the cutting wire and the workpiece, and the narrowest width was quite equal to the diameter of cutting wire.

Secondly, in order to study the influence of cutting current in deep water, the water pressure was adjusted to the water depth of 50 m. The cutting voltage was 50 V, and the cutting speed was 130 mm/min.

The kerf shape is shown in Fig. 14. When the water pressure is higher, the influence of current on the kerf shape is not as obvious as that in shallow water. The shape always presented as "∧" type, and the main difference was the position of the kerf internal notch. According to the underwater arc cutting mechanism, with the raising of the cutting current, the position of the kerf internal notch gradually decreases because the arc's average vertical position decreases.

3.3 The influence of voltage on cutting process

The voltage affects the arc length and width. To study its influence, the cutting voltage was set to 35, 40, and 45 V, respectively.

Firstly, the water pressure was adjusted to the water depth of 0.2 m. The cutting current was 450 A, and the cutting speed was 130 mm/min. The kerf shape is shown in Fig. 15.

The experimental results show that the upper and lower kerf gradually widens with the increase of arc voltage. When the arc voltage was lower, the arc easily extended into the workpiece and the upper kerf became narrower. This effect was similar to that in the condition of large cutting current.

Secondly, in order to study the influence of cutting current in deep water, the water pressure was adjusted to the water depth of 50 and 100 m. The cutting

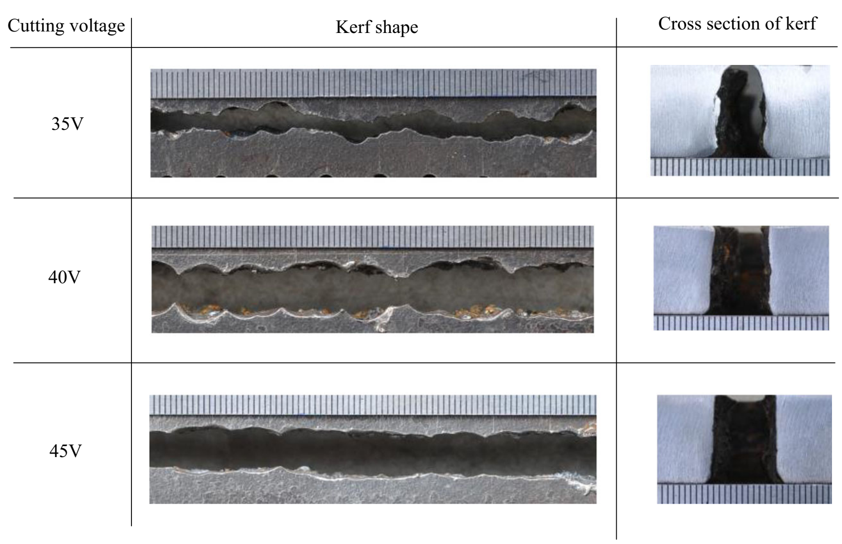


Fig. 15 The kerf shape in different cutting voltage at the depth of 0.2 m

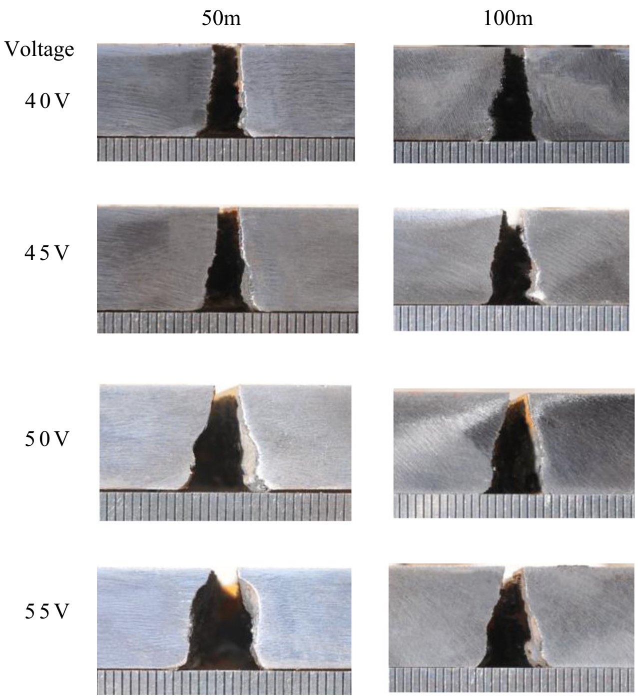


Fig. 16 The cross section of kerf in different cutting voltages

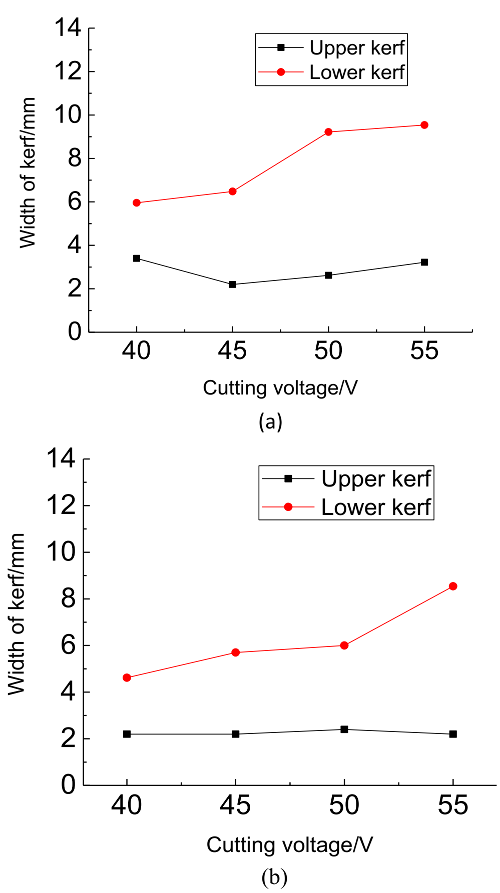


Fig. 17 The upper and lower kerf width with the cutting voltage changing. **a** 50 m. **b** 100 m

voltage was set to 40, 45, 50, and 55 V, respectively; the cutting current was 450 A; and the cutting speed was 130 mm/min. The kerf shape is shown in Fig. 16.

As is shown in Figs. 16 and 17, the arc length became longer and the average vertical position gradually heightened with the increase of the arc voltage. The width of the lower kerf gradually increases; while the width of the upper kerf did not vary a lot.

4 Conclusions

The conclusions are drawn as follows:

1. Besides moving forward with the torch, the arc moves up and down periodically in air. The wire feed speed, cutting speed, and arc voltage decide the vertical position of the arc, which greatly affects the cutting stability. Analysis on the underwater sandwich structure observation and electrical signal shows that there is a high similarity in the air and underwater cutting.
2. With the increased underwater depth, the arc is narrowed and the kerf is accordingly narrowed. The cutting wire end usually extends into the workpiece, and the kerf's upper is approximately equal to that of the cutting wire. At the same time, the average length of broken wire becomes much shorter with the deepening of water.
3. For the cutting current, when the water pressure is low, the kerf shape gradually changes from "∨" type to "| |" type and then "∧" type with the raising of the cutting current; the upper kerf width gradually narrows; and the lower kerf width widens a bit. When the water pressure is high, the change of kerf shape is not as obvious as that in shallow water. With the raising of the cutting current, the shape always presents "∧" type, and the position of the kerf internal notch gradually decreases.
4. As to the cutting voltage, when the water pressure is low, the upper and lower kerf gradually widens with the enhancement of the arc voltage. When the water pressure is high, with the increase of the arc voltage, the arc length becomes longer, the average vertical position gradually rises, and the width of the lower kerf gradually widens, while the width of the upper kerf is still the same as the diameter of the cut wire.

Funding information This study received financial support from the Natural Science Foundation of China (No 51775255), Natural Science Foundation of Jiangsu Province (No. BK20171308), and the Qing Lan Project of Jiangsu province for young and middle-aged academic leaders.

References

1. Masanobu H (1982) Application of consuming electrode water jet cutting technique in underwater nuclear reactor demolition. Bull Jpn Inst Met 21
2. Bach W, Bienia H, Versemann R, Philipp E (2002) High-performance thermal cutting techniques for underwater use. ATW Int. Z Kernenerg 47(4):250–252
3. Frazer I, Fyffe L, Gibson OJ, Lucas B Remotely operated underwater thermal cutting processes for the decommissioning of large North Sea platforms. In: ASME 2002 21st international conference on offshore mechanics and Arctic engineering, 2002. pp 535–542
4. Paton Electric Welding Institute BWI (2007) Underwater wet welding and cutting. Beijing Petroleum Industry
5. Nefedov YN, Danchenko ME (1998) Technology and experience of application of underwater flux-cored wire arc semi-automatic cutting. In: Underwater wet welding and cutting. Woodhead publishing, pp 96–104
6. Danchenko ME (1989) Underwater arc cutting with a cored electrode. Weld Int 3:562–563
7. Gretskii YY, Nefedov YN (1998) Study of peculiarities of underwater flux-cored wire arc cutting without additional supply of oxygen. In: Underwater wet welding and cutting. Woodhead publishing, pp 87–95
8. Masanobu H, Fumikazu T, Munehide K, Yoji O (1977a) On the underwater cutting using a consumable electrode water jet technique—cutting phenomena. J Jpn Weld Soc 46:264–270
9. Masanobu H, Fumikazu T, Munehide K, Yoji O (1977b) On the underwater cutting using a consumable electrode water jet technique—cutting with constant voltage welder. J Jpn Weld Soc 46: 548–552
10. Yu S, Jiang H, Yu H (1981) A study of underwater thick plate cutting technology. J Shanghai Jiaotong Univ (Natural Science Edition):43–52
11. Wu Y, Yu S, Jiang H, Yu H (1984) Investigation of underwater arc cutting and its technological parameters. Journal of Shanghai JiaoTong University 18(6)
12. Haferkamp H, Bach FW, Yoji O, Rachkov M (1994) Climbing robot for underwater cutting. Oceans IEEE 1:602–607
13. Yoji O (1987) Underwater cutting of thin wall stainless steel. Pre-Prints of the National Meeting of JWS Japan Welding Society
14. Tian X, Liu Y, Cai B, Lin R, Liu Z, Sun P (2014) Experimental investigation on electric arc cutting process for casing. Mater Manuf Process 29(29):166–174
15. Wang J, Shi J, Wang J, Li W, Liu C, Xu G, Maksimov SY, Zhu Q (2017) Numerical study on the temperature field of underwater flux-cored wire arc cutting process. Int J Adv Manuf Technol:1–10
16. Shi J, Wang J, Li W, Zhu Q (2017) Research on shape of cut cavity and microstructure of heat affected zone during underwater flux-cored wire arc cutting process. Trans China Weld Inst 38(2):97–100
17. Guo N, Wang M, Du Y, Guo W, Feng J (2015) Metal transfer in underwater flux-cored wire wet welding at shallow water depth. Mater Lett 144:90–92