Hollow Cathode Centered Negative Pressure Arc

An experimental system to stabilize this novel arc was designed, and the arc behavior was monitored and studied through the use of a high-speed image processing system

BY F. JIANG, S. J. CHEN, R. Y. ZHANG, Z. Y. YAN, J. X. WANG, AND Y. M. ZHANG

ABSTRACT

A novel welding arc named hollow cathode centered negative pressure arc (HCCNPA) is proposed in this paper. This is an arc discharge being ignited/maintained at a hollow cathode whose cavity is negatively pressurized. The authors designed an experimental system to stabilize the arc and monitored/studied the arc behavior using a high-speed image processing system. Arc behaviors were studied and correlated to the process parameters. It was confirmed that the negative pressure constricted the arc and elevated the tungsten temperature. The dynamic change in the arc characteristics were reflected in the arc voltage waveform. In addition, the arc length, current, and inner pressure all affected the characteristics of the resultant arc. To examine the distribution of this novel arc as a heat source, stagnation ablation experiments were designed and conducted on Grade D steel workpieces. Analyses on the bead appearance, cross section, and microstructure provided the evidence to support the claim that the resultant arc in the proposed HCCNPA process has a more evenly distributed energy density in the center and a higher energy gradient at the boundary in comparison with the conventional GTA, as have been expected.

KEYWORDS

- Welding Arc
- Arc Contraction
- Hollow Contraction
- Negative Pressure
- Heat Distribution

Introduction

Arc welding is the most widely used joining process and is expected to continue playing an irreplaceable role in metals joining. Among various types of arc welding processes, gas tungsten arc welding (GTAW) offers unique attributes such as superior quality, suitability for almost all metals, and independent control of heat and mass (filler metal). It has become the primary process used for precision joining in applications that require high-quality welds, such as those in aerospace, nuclear, semiconductor, and instrument industries (Refs. 1–4). In this process, the electric arc is established between the tip of a nonconsumable electrode and the workpiece. Heat generated by the arc melts the base metal, forms a liquid weld pool and then joins the two pieces of the base metal together after solidification. As a heat source, the distribution of arc energy on the surface of the workpiece plays an essential role in determining its properties in processing the workpiece to make welds as well as its stability and resultant welding productivity and efficiency. Improving the properties of the arc heat source toward more desirable attributes to produce welds has thus been an active area of research/invention (Refs. 5–11). This paper proposes and explores a novel method to improve the properties of the arc as a heat source.

Basically, one may consider that there are two major approaches to change the energy distribution of the arc, without or with using other (than arc) energy/heat sources. The first one, without using other heat sources, still results in variants of an arc welding process and enjoys the advantages of arc welding. Pulsed gas tungsten arc welding (GTAW-P) is an example in this category, which does the following: 1) uses a repetitive high peak current to establish the penetration and a base current to reduce the heat input and 2) has been found to be effective in achieving greater penetration without increasing the heat input or be effective in reducing the distortion without reducing the penetration, in comparison with using a continuous current (Refs. 12–15). Another example is twin electrode GTAW, which uses two electrodes insulated from each other in a single torch, with the resultant two arcs attracting each other according to the self-induced magnetic fields (Ref. 16). When parallel multielectrodes are used, the energy density is...
further increased (Ref. 17). Recently, arcing-wire GTAW, which establishes a side arc between the tip of the tungsten and the filler metal inside the main arc to transfer part of energy to the filler metal, was developed to attain high depositions with low heat inputs (Ref. 18). Laser-hybrid GTAW (Refs. 19–22) is an example for the second approach where a laser as another heat source has been introduced to alter the energy distribution of the arc.

Hollow cathode vacuum arc welding (HCVAW) is a particular process that changes the arc distribution without using other heat sources and can thus retain certain advantages of traditional arc welding. It introduces gas through the central cavity of its hollow cathode and discharges the gas in the low pressure/vacuum (Refs. 23–25). The special arc discharge mechanism is that for the conventional gas tungsten arc where the discharge occurs at the tip of the cathode. Because of the pressure gradient, the heat from the arc discharge accelerates the arc plasma to an ultrahigh speed when exiting the hollow cathode. The special arc discharge and motion behavior make the hollow cathode vacuum arc have high energy density, penetrability, and stiffness, desirable for nonferrous welding as an alternative to electron beam welding (EBW) in some cases such as welding in space. However, despite the merits brought by the hollow cathode, HCVAW still has several limitations that constrain its applications, including difficulty ionizing the discharge in low pressures and difficulty in maintaining the low pressure in a large region in atmosphere.

To summarize, the authors would like to categorize the approach involving additional heat sources such as laser-arc hybrid welding as an incremental modification. While an incremental modification increases/improves both the density and total heat, it also introduces interactions among multiple heat sources and complicates the controllability. For the equivalent modification without using another energy source to change the total heat such as a plasma arc, the arc density change is made possible by other methods, such as gas constrain as in plasma arc welding and pressure gradient as in HCVAW. However, in both categories using either aforementioned approach, there is no energy reduction. In analysis of existing efforts related to the equivalent modification, HCVAW retains major characteristics of the original GTAW except for the energy density improvements while others result in significant deviations from that of the original GTAW. However, HCVAW has a few limitations, including being difficult to ionize the discharge in low pressures.

In this paper, a hollow cathode with negative pressure in its cavity was
used such that the arc can be ignited in atmosphere. The resultant arc is referred to as hollow cathode centered negative pressure arc (HCCNPA). The paper will center around proving the concept and the feasibility of this novel arc heat source with experimental results for the effects on arc distribution characteristics. As will be illustrated, this process removes the unnecessary/counteractive part of the energy in the center of the heat source and its surrounding region. It is thus a subtractive modification of the arc, different from the incremental and equivalent modifications previously mentioned.

**Principle and Method**

One may argue that an ideal arc welding heat source for fusion welding may be defined as that which just has the right heat to melt the needed amount of metal to form the desired joint but without energy waste to produce detrimental effects on the weld quality. Based on this idealized definition, the ideal heat source should have a suitable energy density (referred to as desired energy density in Fig. 1A) in a region suited for the desired shape of the welded joint and sharply decrease out of this region, as illustrated by the dashed line in Fig. 1A. This ideal distribution, which is a generalized bell shape, differs from the Gaussian distribution as shown by the solid line in Fig. 1A that represents typical energy distribution of a conventional gas tungsten arc (GTA).

To achieve the ideal arc energy distribution, the authors proposed a subtractive modification method for a novel welding arc, HCCNPA. Figure 2 shows the principle of the proposed HCCNPA. In Fig. 2A, there is a conventional GTAW torch without filler metal but a hollow cathode replaces the solid cathode. As illustrated in Fig. 2B, after the arc is ignited in the atmosphere, a negative pressure is formed at the root of the hollow cathode by exhausting gas out of the cavity of the cathode. This negative pressure is the gauge pressure compared with the ambient environment, generated by exhausting gas out of the hollow cathode to create a partial vacuum within it. The intention is to draw part of the ionized gas (arc plasma) into the cavity of the cathode. This is believed to reduce the energy intensity in the arc center helping reshape the arc energy distribution for a generalized bell shape. Figure 2C shows that exhausting gas should continue after the arc burns steadily, to maintain the needed negative pressure to continue absorbing part of the arc plasma.

In a previous study, the authors considered an arc a composite of arc plasma (ionized gas) and electron flow (Refs. 28, 29). The electron flow leaves the tungsten tip along a trajectory to move toward the anode. This trajectory follows the electric field direction. The electron flow ionizes gas on the trajectory to keep flowing; the ionized gas (arc plasma) is electrically neutral and has its own movement characteristic. If there is no gas exhausting, the arc plasma will follow the trajectory of electron flow, gradually flow toward the anode to continuously maintain the ionization by the electron flow as conventional GTA. Therefore, the energy distribution on the anode/workpiece is built by these two parts. In the HCCNPA proposed, with the gas exhausting, the pressure difference drives part of the arc plasma near the central cavity into the hollow cathode. This part of the arc plasma takes away a certain amount of energy that would otherwise also be...
imposed on the workpiece. As a result, the redundant energy in the center of the arc heat source over the ideal generalized bell shape will be reduced. On the other hand, the loss in this part of the arc plasma makes the electron flow to tend to congregate in the center based on the arc minimum voltage principle (Steenbeck’s minimum principle) (Ref. 30). Moreover, the pressure in the center of the arc cathode is lower than in the surroundings, so the arc plasma is further constrained by the environmental pressure. These two effects increase the gradient of the arc energy. The energy reduction in the center together with the increased gradient will tend to produce an energy distribution closer to the ideal shape — a generalized bell.

Figure 3 shows the behaviors of a hollow cathode gas tungsten arc, before and after the negative pressure is applied, under 300-A current, 6-mm tungsten diameter with 1-mm inner diameter, 60-KPa inner pressure, 4-mm arc length, and 10 L/min shielding gas flow rate. The inner pressure is the average pressure in the cavity of the cathode as measured at the exit end of the hollow cathode. From Fig. 3, it is apparent the arc was much more constrained after exhausting the gas. The brightness of the cathode significantly increased, suggesting the migration of the arc plasma into the cathode through the cavity. The presence of the arc plasma in the cavity may have made the inner wall of the hollow cathode also be able to emit electrons.

It should be mentioned that, despite the use of a hollow cathode, the proposed method differs from the HCVAW where the working condition is low pressure/vacuum and the hollow cathode is used to transport the gas to ensure the arc stability. Hence, the proposed HCCNP is different from the HCVA in both the operation principle and the objective to realize. Since the working condition for the proposed HCCNP is atmosphere, the issues with the HCVA, such as being difficult to ionize the discharge in low pressures and maintain low pressures in a large region in atmosphere, no longer exist. To better understand this novel arc for its unique characteristics as a heat source, this work will answer through experiments and analysis how its characteristics are related to different parameters and how the changes in the characteristics affect the energy distribution of the arc as a heat source on the workpiece.

Experimental Procedure

**Experimental Setup**

An experimental system has been established to demonstrate the hollow cathode central negative pressure arc, conduct experiments, and measure the energy distribution. This system, shown in Fig. 4, consists of a pressure system, arcing system, and power and data collection system. The pressure system, which consists of a pressure display, a pressure relief device, a me-
chanical pump, a valve, and connecting tubes, provides a stable and controllable negative pressure to the arcing system. A pressure display is connected with the outlet of the pressure relief device to display the pressure that is used as the representation of the negative pressure in the arcing system. A valve is arranged onto the interface tube between the pressure relief device and the arcing system for easy arc ignition without the negative pressure. The arcing system consists of a gas tungsten arc welding torch, a hollow tungsten cathode, a workpiece, and a water-cooling system that is not given in the figure. The torch is vertically fixed on a welding bench and its position can be adjusted three-dimensionally. The hollow cathode is sealed to the pressure system via the valve. A water-cooled copper block or Grade D steel plate is used as the workpiece in a fixed time. This type of experiment was designed to analyze the effects of negative pressure on the heat distribution. These effects are reflected on the bead appearance, macro metallurgical graph, and microstructure of the weld spot. In all the experiments, pure argon was used as the shield gas with 10 L/min flow rate. Other parameters that were not mentioned previously and changed with experiments are given in Table 1.

To ensure the HCCNPA to be stable and the negative pressure to be constant, the ignition of the arc followed these steps: First, made sure the valve in the pressure system was closed; then started the pumping process to decrease the pressure in the pressure relief device until the preset value was reached. Second, established the arc between the hollow cathode and the workpiece in the atmosphere similarly as for conventional GTAW; then made sure the arc had become stable. Third, turned on the valve to transfer the negative pressure to the hollow cathode. Fouth, kept the mechanical pump in working condition to maintain the stability of the negative pressure in the hollow cathode.

Experimental Procedure

There were two types of experiments involved in this study, the arc tests and stagnation ablation experiments. The arc tests were designed to analyze the arc behaviors, including the shape and electric characteristics, in relation to different parameters. The arc was kept stationary and the workpiece was the water-cooled cooper block. The major parameters included the pressure of the hollow cathode, the current, and the arc length. A high-speed camera was used to image the arc shape and was synchronized with the current and voltage sensors. For the stagnation ablation experiments, an arc ablated a fixed spot of the workpiece in a fixed time. This type of experiment was designed to analyze the effects of negative pressure on the heat distribution. These effects are reflected on the bead appearance, macro metallurgical graph, and microstructure of the weld spot. In all the experiments, pure argon was used as the shield gas with 10 L/min flow rate. Other parameters that were not mentioned previously and changed with experiments are given in Table 1.

In Table 1, AT refers to the arc test experiments. SA refers to the stagnation ablation experiments on 10-mm-thick A283 Grade D steel plates. For the Inner Pressure (KPa), 100 KPa was considered as the atmosphere. Tungsten Type H and S mean hollow and solid tungsten electrodes, respectively. The arc images were taken by the high-speed camera without any filters and the exposure time was set to be small, from 1 to 11 μs.

To ensure the HCCNPA to be stable and the negative pressure to be constant, the ignition of the arc followed these steps: First, made sure the valve in the pressure system was closed; then started the pumping process to decrease the pressure in the pressure relief device until the preset value was reached. Second, established the arc between the hollow cathode and the workpiece in the atmosphere similarly as for conventional GTAW; then made sure the arc had become stable. Third, turned on the valve to transfer the negative pressure to the hollow cathode. Fouth, kept the mechanical pump in working condition to maintain the stability of the negative pressure in the hollow cathode.

Experimental Results and Analysis on Characteristics of HCCNPA

Dynamic Process

Experiments 1 and 2 were designed to examine the effects of the negative pressure on the arc behaviors, including the shape and electric characteristics. The arc tests were designed to analyze the arc behaviors, including the shape and electric characteristics, in relation to different parameters. The arc was kept stationary and the workpiece was the water-cooled cooper block. The major parameters included the pressure of the hollow cathode, the current, and the arc length. A high-speed camera was used to image the arc shape and was synchronized with the current and voltage sensors. For the stagnation ablation experiments, an arc ablated a fixed spot of the workpiece in a fixed time. This type of experiment was designed to analyze the effects of negative pressure on the heat distribution. These effects are reflected on the bead appearance, macro metallurgical graph, and microstructure of the weld spot. In all the experiments, pure argon was used as the shield gas with 10 L/min flow rate. Other parameters that were not mentioned previously and changed with experiments are given in Table 1.

In Table 1, AT refers to the arc test experiments. SA refers to the stagnation ablation experiments on 10-mm-thick A283 Grade D steel plates. For the Inner Pressure (KPa), 100 KPa was considered as the atmosphere. Tungsten Type H and S mean hollow and solid tungsten electrodes, respectively. The arc images were taken by the high-speed camera without any filters and the exposure time was set to be small, from 1 to 11 μs.

To ensure the HCCNPA to be stable and the negative pressure to be constant, the ignition of the arc followed these steps: First, made sure the valve in the pressure system was closed; then started the pumping process to decrease the pressure in the pressure relief device until the preset value was reached. Second, established the arc between the hollow cathode and the workpiece in the atmosphere similarly as for conventional GTAW; then made sure the arc had become stable. Third, turned on the valve to transfer the negative pressure to the hollow cathode. Fouth, kept the mechanical pump in working condition to maintain the stability of the negative pressure in the hollow cathode.

Experimental Results and Analysis on Characteristics of HCCNPA

Dynamic Process

Experiments 1 and 2 were designed to examine the effects of the negative pressure on the arc behaviors, including the shape and electric characteristics. The arc tests were designed to analyze the arc behaviors, including the shape and electric characteristics, in relation to different parameters. The arc was kept stationary and the workpiece was the water-cooled cooper block. The major parameters included the pressure of the hollow cathode, the current, and the arc length. A high-speed camera was used to image the arc shape and was synchronized with the current and voltage sensors. For the stagnation ablation experiments, an arc ablated a fixed spot of the workpiece in a fixed time. This type of experiment was designed to analyze the effects of negative pressure on the heat distribution. These effects are reflected on the bead appearance, macro metallurgical graph, and microstructure of the weld spot. In all the experiments, pure argon was used as the shield gas with 10 L/min flow rate. Other parameters that were not mentioned previously and changed with experiments are given in Table 1.

In Table 1, AT refers to the arc test experiments. SA refers to the stagnation ablation experiments on 10-mm-thick A283 Grade D steel plates. For the Inner Pressure (KPa), 100 KPa was considered as the atmosphere. Tungsten Type H and S mean hollow and solid tungsten electrodes, respectively. The arc images were taken by the high-speed camera without any filters and the exposure time was set to be small, from 1 to 11 μs.

To ensure the HCCNPA to be stable and the negative pressure to be constant, the ignition of the arc followed these steps: First, made sure the valve in the pressure system was closed; then started the pumping process to decrease the pressure in the pressure relief device until the preset value was reached. Second, established the arc between the hollow cathode and the workpiece in the atmosphere similarly as for conventional GTAW; then made sure the arc had become stable. Third, turned on the valve to transfer the negative pressure to the hollow cathode. Fouth, kept the mechanical pump in working condition to maintain the stability of the negative pressure in the hollow cathode.

Experimental Results and Analysis on Characteristics of HCCNPA

Dynamic Process

Experiments 1 and 2 were designed to examine the effects of the negative pressure on the arc behaviors, including the shape and electric characteristics. The arc tests were designed to analyze the arc behaviors, including the shape and electric characteristics, in relation to different parameters. The arc was kept stationary and the workpiece was the water-cooled cooper block. The major parameters included the pressure of the hollow cathode, the current, and the arc length. A high-speed camera was used to image the arc shape and was synchronized with the current and voltage sensors. For the stagnation ablation experiments, an arc ablated a fixed spot of the workpiece in a fixed time. This type of experiment was designed to analyze the effects of negative pressure on the heat distribution. These effects are reflected on the bead appearance, macro metallurgical graph, and microstructure of the weld spot. In all the experiments, pure argon was used as the shield gas with 10 L/min flow rate. Other parameters that were not mentioned previously and changed with experiments are given in Table 1.

In Table 1, AT refers to the arc test experiments. SA refers to the stagnation ablation experiments on 10-mm-thick A283 Grade D steel plates. For the Inner Pressure (KPa), 100 KPa was considered as the atmosphere. Tungsten Type H and S mean hollow and solid tungsten electrodes, respectively. The arc images were taken by the high-speed camera without any filters and the exposure time was set to be small, from 1 to 11 μs.

To ensure the HCCNPA to be stable and the negative pressure to be constant, the ignition of the arc followed these steps: First, made sure the valve in the pressure system was closed; then started the pumping process to decrease the pressure in the pressure relief device until the preset value was reached. Second, established the arc between the hollow cathode and the workpiece in the atmosphere similarly as for conventional GTAW; then made sure the arc had become stable. Third, turned on the valve to transfer the negative pressure to the hollow cathode. Fouth, kept the mechanical pump in working condition to maintain the stability of the negative pressure in the hollow cathode.
pressure on the arc by the hollow cathode. In this group of experiments, the welding current was fixed at 300 A and the arc length remained at 6 mm. In Experiment 1, the inner pressure was 30 KPa when it applied. In Experiment 2, the inner pressure was 100 KPa, considered the atmosphere. The exposure time of the camera was changed in three levels, 11 to 1 μs, to obtain details about the arc behaviors affected by the negative pressure.

In Fig. 5, the red waveform is the voltage from Experiment 1, including the periods before, during, and after the application of the negative pressure. The black waveform is that from Experiment 2, where the negative pressure was not applied, as a comparison. In the experiment without the negative pressure, the voltage first experienced a gradual but slight reduction for approximately 10 s before it tended to be constant. The similar gradual but even slighter reduction in the voltage was also observable from the experiment with the negative pressure. While such gradual reduction may be relatively insignificant, the voltage jump after the application of the negative pressure was pronounced. Further, after the application, there was a 2-s period during which the voltage gradually increased before it followed the gradual slight reduction pattern. These 2 s should be the transition dynamic period for the effect of the negative pressure. Similarly, after the negative pressure was removed before t = 13 s, the voltage dropped significantly. Again, there was a dynamic transition period for the effect of the negative pressure from the dynamics of the pressure system.

Figure 6 is the arc images in the two experiments with 11 μs exposure time. Figure 6A–C is a dynamic experiment that includes a steady-state period with no negative pressure applied (Fig. 6A), dynamic period after the negative pressure was applied (Fig. 6B), and dynamic period after the negative pressure was terminated — Fig. 6C. That is, for example, Fig. 6C is the image taken during the dynamic transition after the pressure was switched from negative to atmosphere. Figure 6D, as a comparison, is the image taken in Experiment 2, with the hollow cathode but no negative pressure ever applied. When there was no negative pressure applied, as can be seen from Fig. 6A, the arc was unconstrained and freely distributed. A small region at the tungsten tip became bright. After the negative pressure was applied and reached the steady state, a significant arc contraction could be observed from the arc column, as can be seen in Fig. 6B. The tungsten tip became significantly brighter. After the negative pressure was removed and reached the steady state, as can be seen in Fig. 6C, the arc resumed to the distribution similar to that before the negative pressure was applied. Figure 6D is the stable arc image without a negative pressure taken at t = 8 s in Experiment 2. As can be seen, the arc distribution and the tungsten brightness are similar to those taken from Experiment 1 before and after the negative pressure application.

From the voltage waveform from Experiment 1 in Fig. 5, the authors
propose to partition the HCCNPA process into six different stages from $t_0$ to $t_6$, as illustrated in Fig. 7. The $t_0$-$t_1$ period is the atmospheric pressure arc stage without the effect from the negative pressure during which the arc voltage gradually decreased slightly. Figure 8 is the arc images in this stage. A gas tungsten arc can be divided into three regions: ionization region, recombination region, and gas fringes (Ref. 31). They may be observed by using different exposure times. As can be seen in Fig. 8A, with 1-μs exposure time, the bright zone in the arc appears rectangular roughly reflecting the ionization region that is the hottest. When the exposure time increased to 3 μs, as shown in Fig. 8B, the bright zone in the arc significantly increased. The workpiece side of the arc also expanded. Comparing Fig. 8A with Fig. 8B, the boundary of the bright zone is more obvious and extended from a rectangle to approximately an acute trapezoid. This boundary, in Fig. 8B, is considered the boundary of the recombination region. As the exposure time further increased to 11 μs, shown in Fig. 8C, the bright zone extended to all the regions of the arc.

The $t_1$-$t_2$ period in Fig. 7 is the arc constricting stage and the corresponding arc behavior can be seen in Fig. 9. In particular, in this stage the negative pressure application started. The arc voltage sharply increased from 13.36 to 14.27 V quickly in approximately 0.05 s. As shown in Fig. 9A, because of the negative pressure in the cavity of the hollow cathode, the brightness in the center of the arc apparently decreased. The bright zone, considered the ionization region, constricted. This phenomenon could be more clearly seen in Fig. 9B, with 3 μs (increased) exposure time, where the bright zone is considered the recombination region. The negative pressure constrained the bright zone in the arc from an acute trapezoid to an acute triangle. This effect of the negative pressure took place within an ultra short period of time, only 0.05 s. However, this change becomes less apparent with a longer (11 μs) exposure time. As can be seen in the series of images in Fig. 9C, the bright zone that is considered the gas fringes had little changes by the application of the negative pressure. In this stage, the bright zone in the tungsten was still at the top. The comparison among three series of images in Fig. 9, shows the ionization region and the recombination region in the arc column were quick in responding to the negative pressure. It is clearly shown that the electron emission area in the cathode and the conducting path decreases with the constraint of these two zones, which means it is more difficult to transfer rated current from cathode to anode. Therefore, for a fixed current, it needs more energy for electron emission and maintaining the more constrained conducting path. The needed voltage thus increases. However, the changes in the gas fringes of the arc column due to the negative pressure in the arc center were less apparent. As will be shown, the effect on the gas fringes of arc column takes a little longer time to take place.

In the next period/stage, i.e., $t_2$-$t_3$ of Fig. 7 named the tungsten temperature increasing stage, the tungsten temperature significantly increased and the negative pressure went through its dynamic transition. As a result, part of the arc plasma started to enter the cavity of the hollow cathode. This part of the arc plasma also heated the cathode. Hence, the bright zone on the tungsten expanded upward from the tip of the tungsten cathode, as can be seen in Fig. 10A. This expanding phenomenon was more obviously seen when the exposure time increased from 1 to 11 μs. It is interesting to note that the ionization and recombination regions were nearly unchanged in this stage, as shown in the series of images in Fig. 10A and B. The gas fringes had a certain restriction in this stage as can be seen by comparing the first and last image in Fig. 10C, which correspond to the start and end instances for this dynamic transition period $t_2$-$t_3$. It is apparent that the negative pressure takes some time to effect the gas fringes — the outer layer of the arc. Moreover, the increases in the brightness and bright area on the hollow tungsten reduce the arc voltage from 14.21 to 13.70 V in approximately 2 s in Fig. 5. The migration of part of the arc plasma into the cathode cavity apparently strengthened the electron emission of the electrode due to the increased temperature and increased area of the surface with sufficient tem-
temperature elevation such that less energy was needed for electrons to escape out of the tungsten surface.

After reaching the stable state in $t_3t_4$, which is named as the stable negative pressure arc stage, the arc voltage continued falling but the rate was greatly reduced. As mentioned previously and as can be seen in Fig. 5, after reaching the stable state, the arc voltage with the negative pressure was parallel with that without the negative pressure. Additionally, the arc voltage with the negative pressure was approximately 1 V higher than that without the negative pressure. There was also a delay from the voltage waveform without the negative pressure because the negative pressure was applied with a delay after the arc was ignited. During the $t_3t_4$ period with slight voltage reduction, the tungsten brightness had a slight increase but the change in the arc shape was insignificant as shown by the image series in Fig. 6B.

Once the negative pressure stops its application, the pressure in the arc center must recover to that with the atmosphere. From the voltage signal, this transition appears to be quick because the arc voltage dropped from 13.60 to 12.72 V in approximately 2.5 s, as marked in Fig. 11. This stage, shown as $t_4t_5$ in Fig. 7, may be referred to as the negative pressure releasing stage. However, despite this significant voltage drop after the removal of the negative pressure, the arc shape as shown in Fig. 11 with 3-μs exposure time had little changes. The bright zone and the brightness of the tungsten also had little changes during this period. It appears the pressure, when changing from low to high in the cathode center of the arc, has little effects on the arc shape, despite the voltage reduction, during the negative pressure release stage.

The arc voltage then rose again after it had decreased to the lowest point. This rising stage, period $t_5t_6$ in Fig. 7, can be referred to as the tungsten temperature decreasing stage. Figure 12 shows the behaviors of the arc and tungsten in this stage. Because of the removal of the negative pressure, the pressures inside and outside the cavity of the hollow cathode became the same. No arc plasma was drawn into the cavity of the hollow cathode. As such, the temperature of the cathode as well as the bright zone of the tungsten tip resumed to those without negative pressure, thus both reduced, as shown in Fig. 12. As a result, the arc voltage increased from 12.72 to 13.34 V. Comparing the first and last image in Fig. 12 clearly shows the arc shape expanded from an acute triangle to an acute trapezoid over this tungsten temperature-decreasing stage. After this transition, the HCCN-PA process returned to the atmospheric pressure arc stage, i.e., the $t_6t_7$ period in Fig. 7.

In summary, comparative experiments with and without negative pressure and analyses of the dynamic changes, as initiated by the application and removal of the negative pressure, suggest three major effects from the negative pressure on the arc: 1) the negative pressure constricts the arc and elevates the tungsten temperature; 2) the dynamic response of the arc to the application of the negative pressure is faster than that to the removal/releasing; and 3) the application and removal/releasing of the negative pressure are both reflected in the arc voltage waveform.

### Arc Length

A comparison between the results...
in Experiments 1 and 3 can examine the effects of the arc length on the HCCNPA. The two experiments were performed with a fixed/same welding current and inner pressure at 300 A and 30 KPa, respectively, but the arc length was different, 4 mm for Experiment 3 and 6 mm for Experiment 1. The comparative experimental results are given in Figs. 13 and 14.

In particular, in Fig. 13, the red line is the voltage waveform from Experiment 1 with 6-mm arc length while the black one is that from Experiment 3 with 4-mm arc length. Both voltage waveforms demonstrated all the six stages, as described previously. First, in general, as the arc length increased from 4 to 6 mm, the arc voltage increased approximately 1 V on average. (This increase is, of course, well understood per the relationship between the arc voltage and arc length.) Second, while the period for the tungsten temperature-increasing stage had no significant difference, the decrease of the voltage was faster in 4-mm arc length than in 6-mm arc length. In the negative pressure-releasing stage, the waveform of the arc voltage had a more volatile ride in the 4-mm arc length condition. The increase in the arc length appeared to have desensitized the response of the arc voltage.

Figure 14 gives the arc images during the tungsten temperature-increasing stage in both experiments with the exposure time set at 11 μs. Per the experiment results previously mentioned, the arc shape and bright zone of the tungsten will both be affected by the negative pressure in the center of the arc cathode in this period. As can be seen in Fig. 14A, for the arc shape, the decrease in the arc length makes constriction of the arc more significant in this stage, compared with the diameter of the arc on the anode/workpiece in Fig. 14B. However, this decrease had less significant effects on the bright zone of the tungsten, which had similar brightness and expansion speed in Fig. 14A, B. Combined with the results of the arc voltage, one may suggest that, as the arc length decreases, the negative pressure in the center of the arc cathode increases its effects on the arc behavior and voltage.

**Inner Pressure and Current**

Experiments 4 and 5 were designed to examine the effects of the inner pressure and current on the hollow cathode arc. While the tungsten in Experiment 4 was solid, it was hollow with 1-mm inner diameter in Experiment 5. In this group of experiments, the welding current was applied at four levels, from 100 to 400 A. The inner pressure was applied at seven levels, from 30 to 100 KPa. In all experiments, the arc length remained at 6 mm. The images from the experiments are given in Fig. 15 where the horizontal and vertical coordinates give the current and inner pressure used, respectively. The arc image in each grid point is the typical arc shape from the stable stage at the current and inner pressure specified by its corresponding horizontal and vertical coordinates. The decrease in the inner pressure indicates an increase in the pressure difference between the hollow cathode and the environment.

As can be seen in Fig. 15, first, by comparing the images from the experiments with the solid tungsten and hollow cathode using 100-KPa inner pressure, their arc shapes and tungsten bright zones under the same current are both similar. Second, the diameter of the arc increases as the current increases. One can easily understand that the stability of the arc should also increase despite the condition under a hollow cathode central negative pressure. As can be seen from the images in the first and second columns in Fig. 15 with 100 and 200 A (relatively small) current, respectively, when the pressure difference increased (inner pressure reduced), the arc became less stable and more deflected. Especially under 100-A current with 30-KPa inner pressure, the arc was obviously deflected by an angle from the tungsten axis. However, when the current increased to 300 A, the resultant arcs became more stable. Of course, as expected, an increase in the pressure difference implied an increase in the arc contraction. This contraction appeared also becoming more apparent as the current increased, as can be seen especially by comparing the difference between the images in the last and first row in the last column for 400 A with that in the first column for 100 A.

In summary, from this group of experiments, one may conclude that, 1) the tungsten type had little effect on the arc shape and tungsten behavior; 2) the increase of the pressure difference implied stronger contraction on the arc but also less stable; and 3) a larger current corresponded to a more stable arc and more obvious effect by the negative pressure.

**Experimental Results and Analysis on Heat Distribution and Its Effect**

**Bead Appearance**

Experiments 6 and 7 are the stagnation ablation experiments designed to examine the heat distribution from the novel arc and the effect on the welded joint made by HCCNPA. Five levels of current were used in both experiments, from 150 to 350 A. The arc length was fixed at 6 mm. The inner
pressure was set as 30 KPa in Experiment 6 while the comparative experiment, Experiment 7, was conducted using a solid tungsten as conventional GTAW. In both types of experiments, the arc ablated at a fixed position on the workpiece for 15 s. The differences in the ablating traces and resultant microstructures will reflect the effects of the negative pressure on the heat distribution of the arc as a heat source to process the workpiece.

Figures 16 and 17 show the appearances of the stagnation ablation by the HCCNPA and a conventional GTA, respectively. They clearly show the ablation region can be divided into two zones, the melt zone (MZ) and the heat-affected zone (HAZ). Comparing the appearances made by the two arcs, when the current was low at 150 A, they had nearly the same sized MZs and HAZs. As the current increased to 250 A and greater, a clear distinction emerged between the results from the two arcs. The MZ by the HCCNPA is significantly smaller than that from the conventional GTA, so as to the ablation region. This result concurs with the result about the increasing effect of an increasing current in amplifying the contraction due to the negative pressure as was demonstrated in Fig. 15.

For further analysis, the diameter of the ablation region was measured. Figure 18A clearly shows the diameter of the MZ from the HCCNPA is significantly smaller than that from the conventional GTA, as to the ablation region. The result is shown in Fig. 18B. The diameter of the HAZ also increased as the current increased. However, the difference in the HAZ diameter from the two arcs was approximately 0.45 mm. Also, the difference did not significantly change with the current as will be explained further.

For the MZ, the heat was imposed by the arc plasma and electron flow. It is commonly believed that the electron flow/current needs to keep ionizing enough arc plasma as its path. The arc plasma, ionized by the electron flow and as its carrier, will be affected by the pressure. The energy contained in the arc plasma changes according to the amperage of the current (actually the electron flow). When the current is relatively small, the electron flow plays a dominant role in determining the arc energy transfer. In such case, the arc will keep the least column cross section and find the shortest way from the cathode to the anode, to minimize the energy consumption based on the arc minimum voltage principle (Steenbeck’s minimum principle) (Ref. 30).

The applied negative pressure may constrain the arc column, but the electron flow needs enough cross section to pass through unimpededly. This counteracts the constraint effect from the negative pressure. Hence, the effect of the negative pressure on the arc contraction is less apparent with a relatively small current than that with a relatively large current.
When the current increased, the diameter of the arc column increased as can be seen in Fig. 15. This increase reduced the counteraction of the electron flow on the contraction due to the negative pressure, and enhanced the constraint of the arc by the negative pressure. In the HCCNPA process, an increase in the current will change the distribution of the arc energy in two ways. First, the constraint on the arc plasma also constrains the electron flow, which moves within it. This means the energy density of the electron flow increases. Second, an increase in the current and the constraint on the arc plasma increases the amount of the energy in the arc plasma. As a result, the MZ was expected to increase more slowly in the HCCNPA than in the conventional GTA as the current increased, as shown in Fig. 18A.

For the HAZ, the input heat was mainly from the gas fringes outside of the MZ and the heat transferred from the MZ. For a given current, the HAZ actually received the same energy from the melted zone in both arc processes. On the other hand, because of the low density of the electron flow (Ref. 31), the energy from the gas fringes was primarily determined by the pressure difference. With a fixed pressure difference, a fixed constraint force was applied in the gas fringes resulting in a fixed reduction in the HAZ diameter compared with the conventional GTA, as can be seen in Fig. 18C.

**Cross Section**

Macro metallurgical graphs of the welds made from Experiment 6 and 7 are shown in Fig. 19. The measurements of the penetration depth, MZ area, and HAZ area are given in Fig. 20. While the MZ area was mainly determined by the total heat input, the penetration was also largely determined by the energy density of the heat input source. Further, the HAZ area was mainly controlled by the gradient of the energy distribution of the heat source. It can be clearly observed in Figs. 19 and 20 that these measurements all increased in both arc processes as the current increased. However, the tendency of the increase was different in each type of measurement. The HCCNPA process achieved much deeper penetration than the conventional GTA and the penetration difference increased as the current increased. As can be seen in Fig. 19, in the conventional GTA, when the current reached 250 A and beyond, the increasing rate of the penetration was reduced, but the growth rate of the weld width was increasing. As a result, the cross-section area of the MZ by the HCCNPA process was the same as that from the conventional GTA. For the area of the HAZ, the increase in HCCNPA process was slower than that in the conventional GTA as the current increased. When the current was 250 A and beyond, with a significant increase in penetration, the area of the HAZ in the HCCNPA was significantly smaller than that from the conventional GTA process. In particular, some defects started to appear in the center of the welded joint in conventional GTA at 250-A current, and increased as the current increased. However, no defect appeared in the welds made by the HCCNPA process when the current changed from 150 to 350 A.

From the previous results and analysis, the MZ area in the two processes was approximately the same. When the current was the same, this appears to be correct because the total energy input from the two processes was approximately the same. However, because of the contraction of the arc due to the negative pressure in the center of the arc cathode, the arc energy density in the proposed process is greater. As such, the penetration was increased. As a result, the MZ width had to reduce. Further, because part of
the arc plasma was absorbed in the center where the arc was the hottest, the energy distribution with greater density was also more even. The defect-free welds by the HCCNPA may be considered as one of the evidences that the energy distribution of the arc center in HCCNPA is more uniform than that in the conventional GTA such that the overheat on the weld metal is reduced or eliminated.

**Microstructure**

The microstructures of the welded joints in Experiments 6 and 7 were also observed. A common understanding is that the welded joint made on A283 Grade D steel, which belongs to mild steel, usually includes three zones, i.e., fusion zone (FZ), HAZ, and unaffected base metal (BM). As shown in Fig. 21, the HAZ may also be divided into four subzones, i.e., fusion boundary in which melted and unmelted metals are mixed, coarse-grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ), and intercritical HAZ (ICHAZ) (Refs. 32, 33).

The metallographic structures of typical welded joints were examined using a confocal laser-scanning microscope. Figure 22 gives the metallographic structures of the welded joint made using the HCCNPA process with 350-A current while Fig. 23 is those from the comparative conventional GTA process with the same current. The images from A to E are from different zones of the joint. The metallographic structure characteristics change obviously from A to E when away from the fusion zone.

Comparing Figs. 22A and 23A clearly indicates the grain size distribution in Fig. 22 by the HCCNPA was more uniform than that in Fig. 23 by the comparative conventional GTA. The peak temperature in the weld pool was one of the key factors that controlled the microstructure of the resultant welds. Overheating promoted the formation of coarse grains and defects and an even temperature distribution improved the uniformness of the microstructure and grain size in their distributions. Since the difference in the heat source was the only minimal difference in the two comparative experiments, the improved uniformness of the grain size distribution clearly suggests a more uniform temperature distribution in the weld pool. Of course, this directly implies an effective reduction in the peak temperature, thus an effective reduction in the energy density in the center of the heat source by the proposed arc in comparison with the comparative conventional arc.

The microstructure is also affected by the heating speed/temperature gradient. The preceding comparison on macrostructures shows the HAZ diameter and area by the HCCNPA are smaller than those by the comparative conventional arc. The microstructure comparison between Fig. 24B, C and Fig. 25B, C also shows that the grains in the fusion boundary and coarse-grained HAZ by the HCCNPA are finer than those by the comparative conventional arc, especially in the coarse-grained HAZ. The finer grains in both subzones indicated the energy gradient at the heat source boundary in the HCCNPA was higher than that in the comparative conventional arc as has been suggested by the improved/reduced arc fringes in Figs. 9 and 10.

As such, microstructure analysis provided the support from the resultant welds to validate that the resultant arc in the HCCNPA process has a more evenly distributed energy density in the center and a higher boundary energy gradient compared with the conventional GTA, as had been expected.
Conclusions

An innovative arc heat source for GTAW, i.e., hollow cathode centered negative pressure arc, has been proposed and experimentally demonstrated in this study. The dynamic responses to the application and releasing of the negative pressure in the hollow cathode, as well as the effects of the major process parameters on the resultant arc characteristics, were analyzed. The weld joints made by the HCCNPA were used to reflect the energy distribution of the resultant arc.

From the experimental results and comparative analysis, the following can be concluded.

1. The application of the negative pressure in the hollow cathode constrains the arc in the atmosphere and enhances the electron emission in the cathode as reflected in the arc shape and voltage waveform.

2. The tungsten type (solid or hollow) has no significant effects on the arc behaviors but reducing arc length, increasing the current, and increasing the pressure difference all enhance the constraint ability.

3. The resultant welds by HCCNPA have larger penetration and smaller HAZ area but similar MZ area in comparison with those by the conventional GTA. The differences in penetration and HAZ area increase as the current increases.

4. According to the microstructure analysis, the HCCNPA produces finer and more uniform grains in the fusion zone, fusion boundary, and coarse-grained HAZ than the comparative conventional arc, validating that the HCCNPA has a more evenly distributed energy density in the center and a higher energy gradient at the boundary.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grant No. 51505008) and Chaoyang District Postdoctoral Research Foundation (Grant No. 2014zz-02).

References


