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Influence of Energy Ratio of Hybrid Heat Source on Residual Stress Distribution of 7A52 Aluminum Alloy VPPA-MIG Hybrid Welding

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Variable Polarity Plasma Arc-Metal Inert Gas (VPPA-MIG) welding process is a new hybrid welding process with broad application prospects for aluminum alloy structure in the fields of aerospace manufacturing, transportation and others. The heat source of the hybrid welding process is composed of VPPA heat source and MIG heat source. When the total input energy of VPPA-MIG hybrid heat source is constant, the different energy ratio of VPPA arc and MIG arc affects not only the forming effect of hybrid weld, but also the stress distribution of hybrid welding joint. Hole-drilling method was used to analyze the influence of the ratio of VPPA and MIG arc energy on the distribution of welding residual stress in the process of 10 mm 7A52 aluminum alloy VPPA-MIG hybrid welding. The results show that the peak magnitude of hybrid welding residual stress increases with the increase of the ratio of VPPA arc energy. Considering the appearance of weld forming, VPPA-MIG hybrid welding parameters of 7A52 aluminum alloy are optimized on the basis of the distribution characteristic of residual stress. When the ratio of VPPA arc energy is selected between 35% and 40%, the peak magnitude of transverse residual stress is (in the direction vertical to the weld) no more than 92.0 MPa, and the peak magnitude of longitudinal residual stress(in the direction parallel to the weld) is no more than 234.3 MPa. It shows that the VPPA-MIG hybrid welding with optimized parameters can not only produce weld joint with satisfied macroscopic appearance, but also avoid high peak magnitude of residual stress.

Keywords: ratio of energy, variable polarity plasma arc-MIG hybrid welding, residual stress, appearance of weld forming

1 Introduction

In the welding of aluminum alloy structure, plasma arc welding is considered as efficient welding methods [1-4]. When continuously combined with electrical and electronic technology, the manufacturing level of aluminum alloy welding structure can be improved greatly [5-8]. However, vertical welding is generally used in plasma arc welding method, and the range of welding parameters is narrow. Both of them limit the application of this welding method to a certain extent. In order to further improve the welding level of aluminum alloy structure, the researchers have combined plasma arc welding method with traditional metal inert gas (MIG) welding method to form plasma arc - metal inert gas hybrid welding method [9-11]. VPPA-MIG hybrid welding is a new kind of plasma arc hybrid welding method. VPPA-MIG hybrid welding process has the advantages of concentrated energy, large arc straightness, high penetration depth and cathode cleaning ability of VPPA welding, and also with high welding efficiency and wide range of technological parameters of MIG welding.

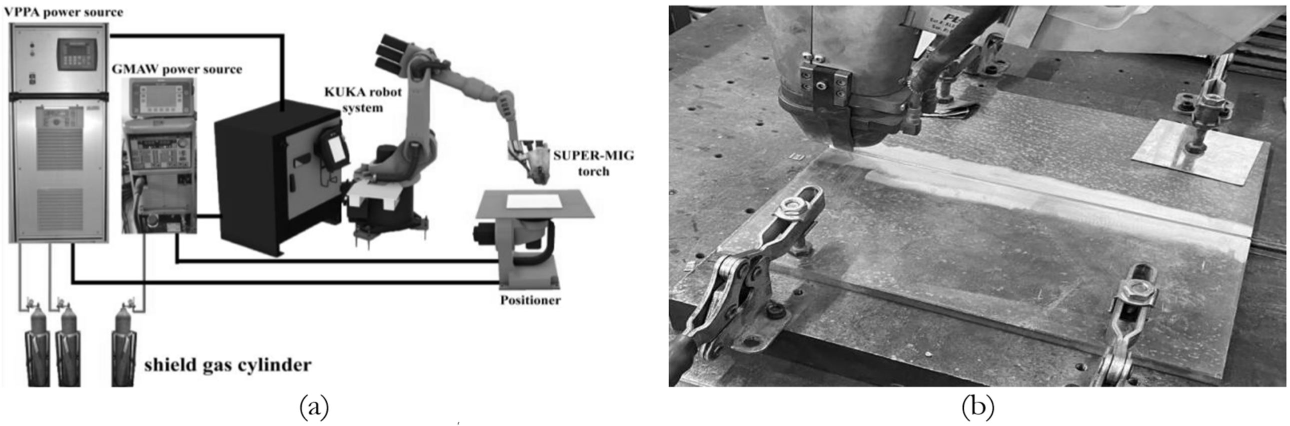
7A52 aluminum alloy is an important welding structural material in aerospace manufacturing and other fields because of its high strength and good welding performance. VPPA-MIG hybrid welding process has broad application prospects for high-efficiency and high-quality welding of aluminum alloy, and the advantages of VPPA-MIG hybrid welding are obvious in the welding of medium-thick plate of high-strength aluminum alloy[12-13]. Especially, this welding method can make the 10mm thick high strength aluminum alloy plates form double side welding with high welding speed through single layer and single pass welding, thus it greatly improves the welding production efficiency [14-15]. However, VPPA-MIG hybrid welding has a hybrid heat source, and its welding energy is more concentrated than that of MIG welding arc. The aluminum alloy medium-thick plate is welded once through the welding method, which leads to the complicated distribution of residual stress and the larger residual stress value in the welded joint that brings a certain challenge to the safety of welded structure. In order to avoid these problems and make full use of the advantages of VPPA-MIG hybrid welding for aluminum alloy medium-thick plates, it is of great theoretical and practical significance to investigate the distribution of residual stress and its influencing factors in the process of VPPA-MIG hybrid welding.

At present, much research has been done on the residual stress analysis of aluminum alloy MIG welding and hybrid welding related to MIG welding. Residual stress and strain in MIG butt welds in 5083-H321 aluminium was measured and analyzed by synchrotron diffraction strain scanning [16]. The residual stress distribution on both sides of the weld is uneven, and the peak magnitude of transverse residual stress and longitudinal residual stress reach 50MPa and 90MPa respectively. Literature [17-18] analyzed the residual stress in laser-MIG hybrid welding for aluminum alloy. Both of them found that the peak magnitude of welding residual stress will appear in the weld area and its adjacent area, and peak magnitude is higher than that of MIG welding. The distribution characteristics of residual stress in aluminum alloy VPPA-MIG hybrid welding have been obtained in literatures [19-20]. In particular, Sun et al. [21-22] accurately analyzed the generation process and distribution law of residual stress in 7A52 aluminum alloy VPPA-MIG hybrid welding by using the method of thermal elastic plastic finite element numerical calculation. However, these results are obtained under the specific hybrid welding parameters. In the process of VPPA-MIG hybrid welding, the heat source to melt metal comes from the hybrid heat source composed of VPPA arc heat source and MIG arc heat source. The stiffness of VPPA arc is large and the heating energy of arc is concentrated, which makes the heating area of aluminum alloy plate relatively narrow. While the deposition efficiency of MIG arc is higher, the heating energy of arc is relatively divergent, so that the heating area of aluminum alloy plate is relatively wide. When the total energy input of VPPA-MIG hybrid heat source is constant, the different energy ratio of VPPA arc and MIG arc affects not only the forming effect of hybrid weld [23-24], but also the distribution of residual stress in hybrid welded joint. At present, there is a lack of research on the effect of hybrid heat source energy ratio on the residual stress distribution of aluminum alloy VPPA-MIG hybrid welded joint. Therefore, it has an important guiding role in the control of hybrid welding technology to investigate the effect of hybrid heat source energy ratio on the residual stress distribution of 7A52 aluminum alloy VPPA-MIG hybrid welding, which can lay a foundation for further promotion of VPPA-MIG hybrid welding technology.

In this work, different welding parameters were set to obtain different energy ratio of VPPA and MIG arc under the conditions of constant total input energy of VPPA-MIG hybrid heat source. Hole-drilling method was used to analyze the influence of the ratio of VPPA and MIG arc energy on the distribution of welding residual stress in the process of 10 mm 7A52 aluminum alloy VPPA-MIG hybrid welding. Considering the appearance of weld forming, the optimized hybrid parameters were abtained, which can not only produce weld joint with satisfied macroscopic appearance, but also avoid high peak magnitude of residual stress.

2 Experiment and research method

This experiment is not innovative, but has engineering application value. In experiment, 7A52 aluminum alloy (chemical compositions as shown in Tab. 1.) plates whose length, width and height is 250 mm, 100 mm and 10 mm respectively were used as base metal to complete VPPA-MIG hybrid butt welding. VPPA-MIG hybrid welding system [25] and the schematic diagram of hybrid welding process is shown in Fig. 1. The speed of hybrid welding was 400 mm / min. The type of welding wire was ER 5183 with diameter of 1.6 mm. Thorium tungsten electrode with diameter of 3.2 mm was used as VPPA electrode, and the distance between nozzle and workpiece was 10 mm. The duration ratio of positive and negative polarity of VPPA arc was 17 ms: 3 ms. Plasma gas and MIG protection gas were surrounded by the whole protective gas, all of which are pure argon. The flow rate of plasma gas was 3.5L / min, the flow rate of MIG protection gas was 23 L / min, and the flow rate of whole protection gas flow was 40 L / min.



(a) (b)

Fig. 1 *VPPA-MIG hybrid welding system and the schematic diagram of hybrid welding process, (a) hybrid welding system (b) hybrid welding process*

***Tab. 1** Chemical compositions of 7A52 aluminum-alloy (percent by weight)*

Element	Zn	Mg	Mn	Cu	Cr	Ti	Zr	Fe	Si	Al
Content	4.73	2.71	0.32	0.08	0.18	0.09	0.07	0.28	0.22	Remainder

As for the VPPA-MIG hybrid welding, the heat input of the hybrid arc to the workpiece E(kJ·cm^{-1}) is compounded by the heat of the VPPA arc and the heat of the MIG arc, as shown in equation (1)[14]. The energy ratios of the two arcs marked as $E_{Z\text{-VPPA}}$ and $E_{Z\text{-MIG}}$ is shown in equation (2) and (3) respectively.

$$E = E_{\mathrm{VPPA}} + E_{\mathrm{MIG}} = \eta_{\mathrm{VPPA}} \frac{U_{\mathrm{VPPA}} I_{\mathrm{VPPA}}}{v} + \eta_{\mathrm{MIG}} \frac{U_{\mathrm{MIG}} I_{\mathrm{MIG}}}{v} \tag{1}$$

$$E_{\mathrm{Z-VPPA}} = \frac{E_{\mathrm{VPPA}}}{E} \times 100\% \tag{2}$$

$$E_{\mathrm{Z-MIG}} = \frac{E_{\mathrm{MIG}}}{E} \times 100\% \tag{3}$$

In the equations (1), (2) and (3), E_{VPPA} and E_{MIG} are the heat input of VPPA and MIG arc respectively, and η_{VPPA} and η_{MIG} are the power coefficients of VPPA and MIG arc respectively, η_{VPPA} is about (0.55~0.6), η_{MIG} is about (0.65~0.7)[14]. U_{VPPA} and U_{MIG} are VPPA arc and MIG arc voltage respectively, and I_{VPPA} and I_{MIG} are VPPA arc and MIG arc current respectively. v is the speed of welding.

In order to accurately analyze the influence of different energy (heat input) ratio of VPPA arc and MIG arc on the distribution of residual stress after hybrid welding, the hybrid welding parameters of 7A52 aluminum alloy plates were reasonably selected as shown in Tab. 2, which could obtain the same hybrid heat input and different energy ratios of the two kinds of arc.

***Tab. 2** VPPA-MIG hybrid welding parameters for 7A52 aluminum alloy*

Experimental groups	Kinds of Arc	Positive polarity current I_+ / A	Negative polarity current I_- / A	Average current I_{av} / A	Voltage U / V	Effective coefficients of arc η	Total energy E (kJ·cm^{-1})	ratio of energy E_z (%)
1	VPPA	120	144	128.4*	21.2	0.6	11.20	22.3
	MIG	-	-	350	25.5	0.65		77.7
2	VPPA	130	182	139.1*	25.9	0.6	11.14	29.1
	MIG	-	-	335	24.2	0.65		70.9
3	VPPA	140	196	149.7*	28.3	0.6	11.15	34.2
	MIG	-	-	320	23.5	0.65		65.8
4	VPPA	150	210	160.4*	29.8	0.6	11.14	38.5
	MIG	-	-	305	22.9	0.65		61.5
5	VPPA	160	224	171.1*	30.7	0.6	11.13	42.6
	MIG	-	-	290	22.6	0.65		57.4
6	VPPA	170	238	182.2*	31.2	0.6	11.18	45.8
	MIG	-	-	275	22.4	0.65		54.2
7	VPPA	180	252	192.5*	31.7	0.6	11.16	49.4
	MIG	-	-	260	22.3	0.65		50.6
8	MIG (root layer)	-	-	212	22.9	0.65	11.10	61.5
	MIG (top layer)	-	-	309	29.8	0.65		38.5

Where:

*…The root mean square current of VPPA arc.

At present, owing to the technical mature, hole-drilling method and X-ray diffraction method are two kind of methods commonly used for the measurement of residual stress. For the welded structure, due to the convex surface shape in the weld and its adjacent area, it is impossible to measure the residual stress by X-ray diffraction method. Therefore, the hole-drilling method is often used to measure the residual stress of the whole welded structure. Under normal circumstances, the distribution of residual stress in the middle part of the welded structure is relatively stable. On the middle cross section of each hybrid welded specimen, five measuring points on the left and right sides of the weld seam were symmetrically taken and were 0 mm, 6 mm, 20 mm, 45mm, and 60 mm from the center of the weld seam, which were located in weld zone, fusion zone, heat affected zone and base metal zone [14], as shown in Fig. 2. According to the relevant requirements in ASTM standards, hole-drilling method was used to measure the transverse welding residual stress and longitudinal welding residual stress at each measuring point.

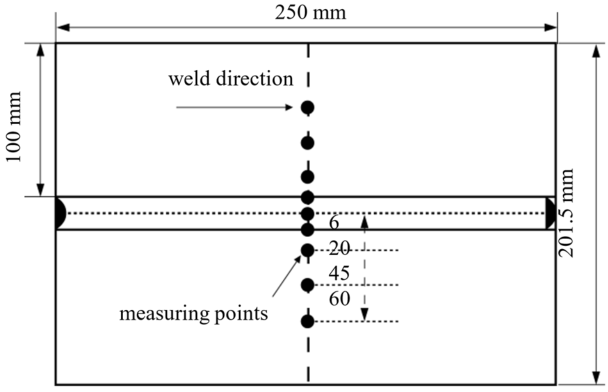


Fig. 2 *Distribution of welding residual stress measuring points*

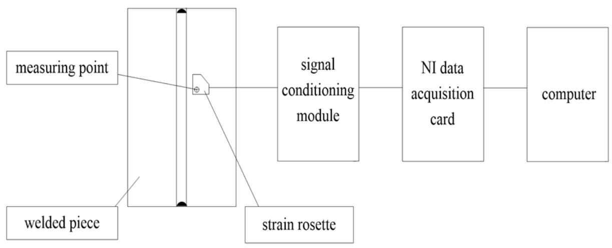


Fig. 3 *The hardware of welding residual stress testing system*

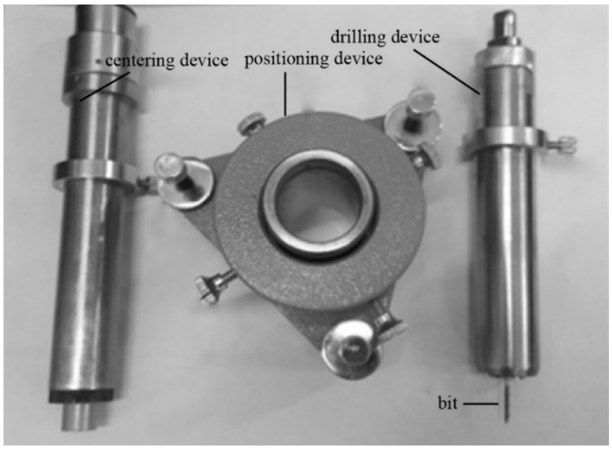


Fig. 4 *Hole-drilling equipment*

According to the principle of measuring residual stress by hole-drilling method, a system of welding residual stress measurement was established. The hardware of the testing system mainly consists of an industrial computer, sensor, NI data acquisition card, and drilling device as shown in Fig. 3. The type of sensor is a resistance strain gauge with the BE120-2CA-K model. The data acquisition card is a model of the PXIe-4330 board card produced by the NI Company. The drilling device was selected in the experiment, including positioning device, centering device and drilling device, as shown in Fig. 4. The model of electric drill is J1Z-AN-6 and its rotational speed is 0 - 1400 r / min. The software of the testing system is based on the hole-drilling method and is written by the virtual instrument LabVIEW. It can collect, filter, display, store the strain signal and complete the calculation of transformation from strain to stress.

After pasting the right angle strain rosette composed of BE120-2CA-K resistance strain gauges on the position to be measured, referring to Fig. 5, a small through-hole with radius a [26] was drilled at the measured point. Since the original stress balance state is destroyed, slight deformation will occur around the small hole. The residual stress at the measured position can be obtained by computation according to the measured strain release, as shown in equation (4).

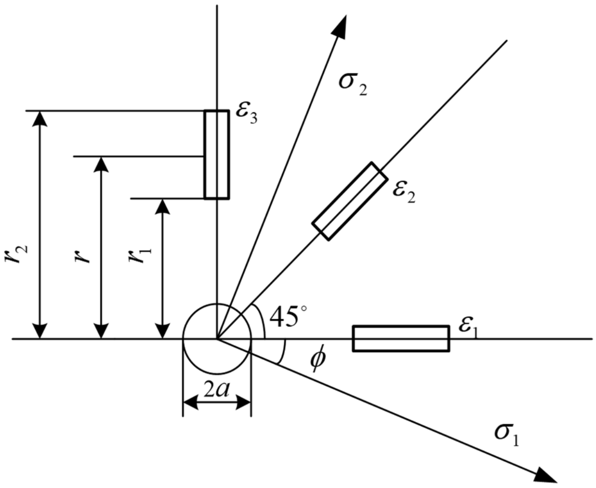


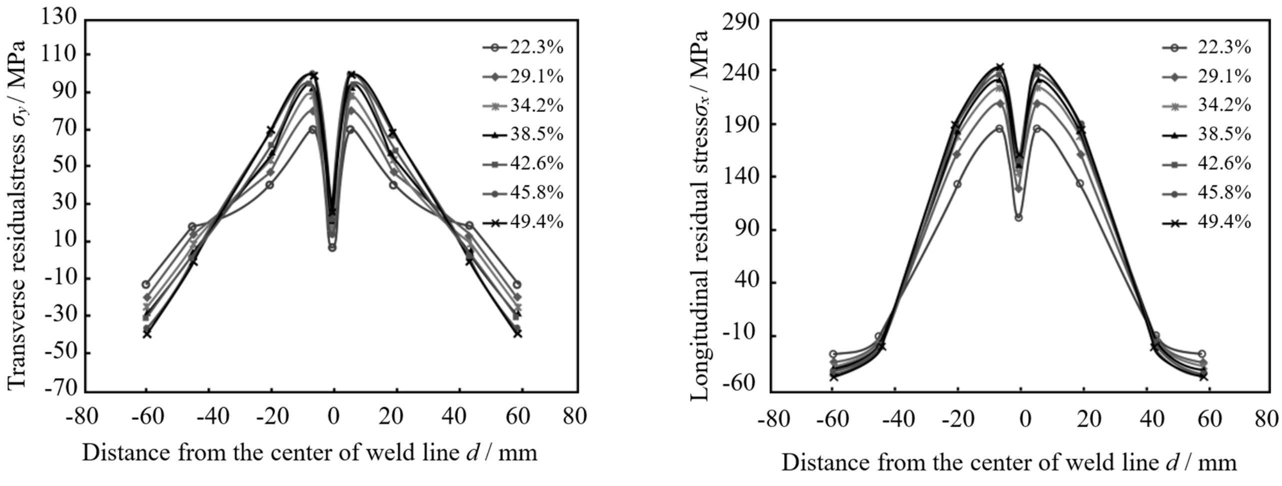
Fig. 5 *Schematic diagram of residual stress measurement by hole-drilling method*

$$\begin{cases} \sigma_{1,2} = \dfrac{1}{4A}(\varepsilon_0 + \varepsilon_{90}) \pm \dfrac{\sqrt{2}}{4B}\sqrt{(\varepsilon_0 - \varepsilon_{45})^2 + (\varepsilon_{90} - \varepsilon_{45})^2} \\ \tan 2\phi = \dfrac{\varepsilon_0 + \varepsilon_{90} - 2\varepsilon_{45}}{\varepsilon_0 - \varepsilon_{90}} \end{cases} \tag{4}$$

In the equation (4), ε_1, ε_2 and ε_3 are the strain release values measured by the strain of 0°, 45° and 90° respectively. A and B are strain release coefficients. ϕ is the angle between principal residual stress σ_1 and strain gauge in the direction of 0° (clockwise direction is positive). σ_1 and σ_2 are principal residual stresses.

3 Results and analysis

After VPPA-MIG welding, the weldseam on the surface of every welded specimen was smoothed with grinding wheel and sandpaper, and then the whole surface of Welded specimen was cleaned with 99.7% ethanol and 99.5% acetone. The distribution of transverse residual stress and longitudinal residual stress of 10 mm 7A52 aluminum alloy VPPA-MIG hybrid weldment under different energy ratios of VPPA arc was measured and obtained by hole-drilling method, as shown in Fig. 6.



(a) (b)

Fig. 6 *Distribution of residual stress for 10 mm 7A52 aluminum alloy hybrid welding plates under the different ratios of VPPA arc energy, (a) transverse residual stress (b) longitudinal residual stress*

As seen from Fig. 6, it is found that, under the condition of the same heat input of VPPA-MIG hybrid welding and different energy ratio of two kinds of arc, the distribution law of transverse residual stress and longitudinal residual stress of 7A52 aluminum alloy VPPA-MIG hybrid weldment is similar, and two kinds of residual stress are basically symmetrical on both sides of the weld centerline. Tensile stress appears in the central region of weld (from weld zone to heat affected zone), and the maximum tensile stress appears in fusion zone, while the compressive stress appears in the zone of base metal. The peak magnitude of longitudinal residual stress is higher than that of transverse residual stress. The distribution characteristics of residual stresses are consistent with those obtained in literature [25] and can be explained as follows.

In the process of VPPA-MIG hybrid welding, no matter what the energy ratio of VPPA arc is large or small, the hybrid heat source is relatively concentrated than the heat source of single MIG welding, which high temperature heating area is narrow, and the heat is conducted from the weld center to both sides, so that the heat of the weld and its adjacent area is concentrated, and the temperature gradient is large, resulting in high stress in those areas of weldment. From the microscopic point of view of weldment material [14], the microstructure of fusion zone and heat affected zone are both very uneven, in which the internal stress are large. The weld zone is coarse equiaxed grain zone, and the internal stress is smaller than that of fusion zone and heat affected zone, but because of the coarse grain, the internal stress of weld zone is larger than that of base metal zone. The internal stress in the hybrid weldment has the characteristics of its own balance, which makes the residual stress reach the maximum in the fusion zone, and then gradually decrease from the heat affected zone to the base metal zone, and the compressive stress forms in the base metal zone. Finally, the area of the tensile stress on the same section is equal to the area of the compressive stress. However, with the change of VPPA arc energy ratio, the peak magnitude of stress of weld and its adjacent area will also change.

In the process of VPPA arc energy ratio increased from 22.3% to 49.4% (about 20% to 50%), the peak magnitude of transverse residual stress and longitudinal residual stress of hybrid weldments will increase with the increasing of VPPA arc energy ratio. The peak magnitude of transverse residual stress will be changed from 65.8 MPa→79.2 MPa→ 87.1 MPa→92.0 MPa→94.1 MPa→97.8 MPa→98.3 MPa, and the peak magnitude of longitudinal residual stress will be increased from 186.7 MPa→211.2 MPa→225.6 MPa→234.3 MPa→237.9 MPa→244.5 MPa→245.5 MPa. In the process of the peak magnitude of residual stress being increased, the peak magnitude of transverse residual stress and longitudinal residual of hybrid weldments will be increased obviously when the VPPA arc energy ratio is increased by about 10%. The gradual increase of the peak magnitude of hybrid welding residual stress is explained as follows.

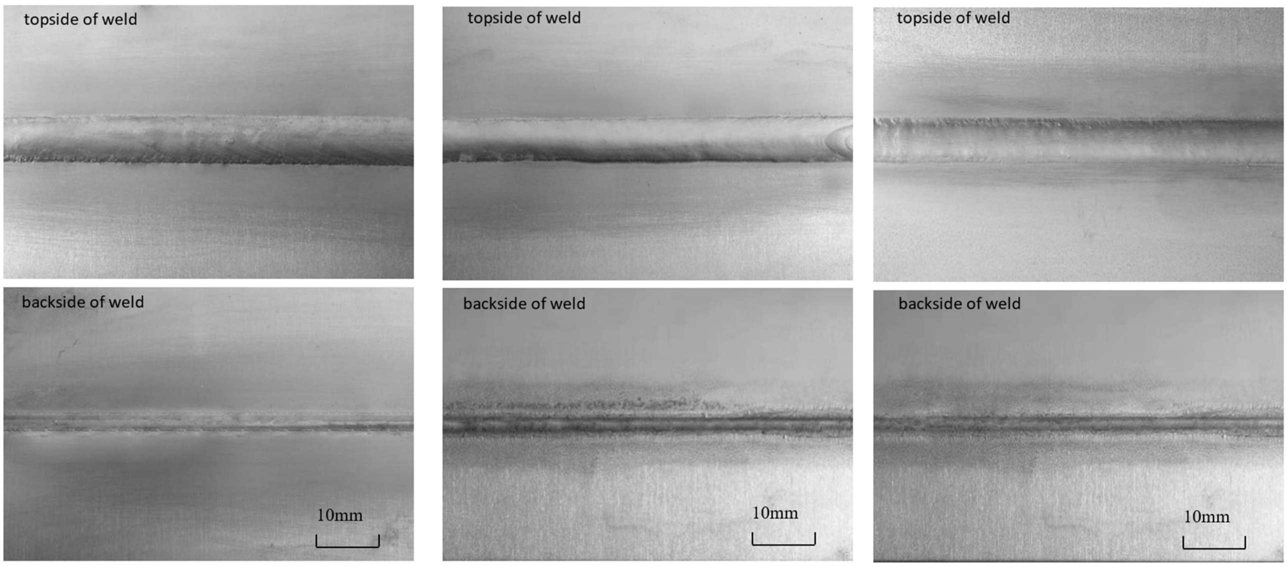
Because of special structure of hybird welding torch, in which the plasma welding torch is perpendicular to the workpiece plane, an included angle of 16° is formed between MIG welding torch and VPPA welding torch and the distance between the two welding torches is 8 mm, the energy of VPPA arc heat source is more concentrated than that of MIG arc heat source in the process of 7A52 aluminum alloy VPPA-MIG hybrid welding [14]. On the premise that the total input energy of the hybrid heat source is fixed, the larger the ratio of VPPA arc energy is, the more concentrated the total input heat is, and the narrower the high temperature heating area is [23].

The concentrated hybrid heat is transferred from the weld center to both sides, which makes the heat input from the weld and its adjacent areas (fusion zone and heat affected zone) concentrated and the temperature gradient increases, which intensifies the non-uniformity of local heating and leads to the increase of stress in the concentrated heating area and the appearance of larger stress peak value.

The yield strength of base metal is about 458 MPa, and the tensile strength of base metal is about 493 MPa. The tensile strength of VPPA-MIG hybrid welded joint is about 304 MPa under specific welding parameters for good weld forming effect [14, 25]. The peak magnitude of longitudinal residual stress is higher than that of transverse residual stress, and the peak magnitude of longitudinal residual stress is compared with yield strength of base metal and the tensile strength of VPPA-MIG hybrid welded joint. It is found that, in the process of VPPA arc energy ratio increased from 22.3% to 49.4%, The minimum peak magnitude of longitudinal residual stress reaches 40.8% of the yield strength of base metal and 61.4% of the tensile strength of hybrid welded joint respectively, and the maximum residual stress peak reaches 53.6% of the yield strength of the base metal and 80.8% of the tensile strength of the hybrid welded joint respectively. It can be seen that the greater the ratio of VPPA arc energy, the greater the threat of residual stress peak to hybrid welded joints. Therefore, when Optimizing hybrid welding parameters, excessive energy ratio of VPPA arc cannot be selected to avoid excessive residual stress peak value and stress concentration, which will threaten the reliability of the joint [27].

In summary, in the process of 7A52 aluminum alloy VPPA-MIG hybrid welding, when the VPPA arc energy ratio is increased from 20% to 50%, the peak magnitude of hybrid welding residual stress will be increased with the increase of the VPPA arc energy ratio. The greater the ratio of VPPA arc energy is, the greater the threat of residual stress peak to hybrid welded joints is. When the VPPA arc energy ratio is increased about 10%, the peak magnitude of hybrid welding residual stress will have a relatively obvious trend of increase.

According to the welding parameters shown in Table 2, 10 mm 7A52 aluminum alloy plates were welded by VPPA-MIG method. After welding, it was found that when VPPA arc energy accounted for 34.2%, 38.5% and 42.6% respectively, the corresponding macroscopic appearance of weld formation was better, as shown in Fig. 7.



(a) (b) (c)

***Fig. 7** Images of the hybrid welding weld seam for 10 mm 7A52 aluminum alloy hybrid welding plates under the different ratio of VPPA arc energy, (a) the ratio of VPPA arc energy is 34.2%, (b) the ratio of VPPA arc energy is 38.5%, (c) the ratio of VPPA arc energy is 42.6%*

According to Fig. 7, it is found that the macroscopic appearance of the weld in subgraphs a, b and c are all good. There are no undercut and hump defects, the topside of the weld has uniform fish scale, and the backside of the weld is smooth and uniform. According to the distribution of hybrid welding residual stress shown in Figure 6 above, the peak magnitude of hybrid welding residual stress will increase with the increase of the ratio of VPPA arc energy. When the VPPA arc energy ratio is 34.2%, 38.5% and 42.6%, the corresponding peak magnitude of hybrid welding residual stress is close, which is less than the peak magnitude when the ratio of VPPA arc energy is 45.8% and 49.4%. Therefore, VPPA-MIG hybrid welding with the ratio of VPPA arc energy of 34.2%, 38.5% and 42.6% for 10 mm 7A52 aluminum alloy plate can not only obtain good macroscopic appearance of weld, but also avoid excessive residual stress peak value and the local concentration of stress, which can improve the reliability of hybrid welding joint.

Considering the effect of weld forming and the rationality of residual stress distribution, the welding parameters of VPPA arc energy between 35% and 40% are selected to weld 7A52 aluminum alloy plates. VPPA-MIG welding can be used to obtain not only the weld with good macroscopic appearance, but also the residual stresses not higher than 92 MPa (about 30.3% of the tensile strength of the hybrid welded joint) in the transverse direction of the weld and not higher than 234.3MPa (about 77.0% of the tensile strength of the hybrid welded joint) in the longitudinal direction of the weld. Therefore, when the ratio of VPPA arc energy is between 35% and 40%, the weld joint with satisfied macroscopic appearance can be obtained, and the peak magnitude of residual stress will not be too high, which can avoid local stress concentration and improve the reliability of the hybrid welded joint.

According to the welding parameters of group 4 and group 8 in Table 2, the residual stresses of VPPA-MIG welding and conventional MIG welding are compared On the basis of consistency of total input energy, as shown in Fig. 8.

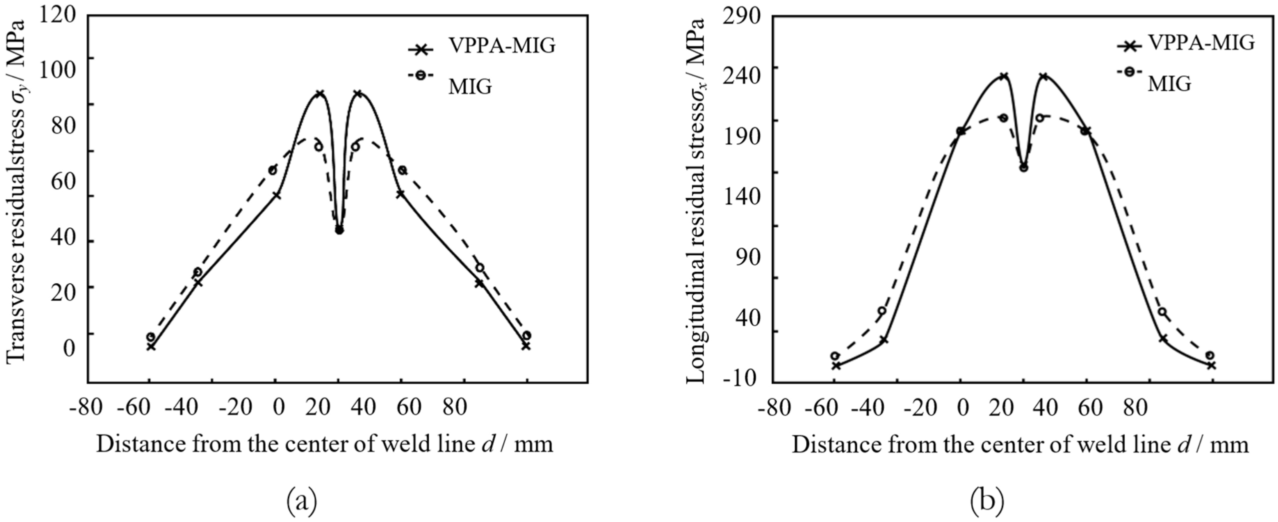


Fig. 8 *Comparison of residual stress distribution for VPPA-MIG hybrid welding and MIG welding of 10 mm 7A52 aluminum alloy, (a) transverse residual stress (b) longitudinal residual stress*

As seen from Fig. 8, it is found that, the distribution of residual stress of 7A52 aluminum alloy single MIG welding along both sides of the weld is similar to that of hybrid welding. The maximum tensile stress appears near the fusion zone. The peak magnitudes of transverse residual stress and longitudinal residual stress are 68.2 MPa and 191.0 MPa respectively, which are lower than the maximum transverse residual stress (92.0 MPa) and longitudinal residual stress (234.3 MPa) of hybrid welding, but the high stress zone is wider than that of hybrid welding.

The above phenomenon is due to the fact that the arc energy of hybrid welding is more concentrated than that of single MIG, and the concentration of heat source energy makes the high-temperature heating area on both sides of hybrid welding seam narrower than that of MIG welding. The temperature gradient of hybrid welding seam area is large, which results in more serious local heating heterogeneity [25]. Besides, conventional MIG welding requires double-layer welding after being beveled (as shown in Fig. 9), and the second layer (top layer) welding has a certain heat treatment effect on the first layer (root layer) welding, which is beneficial to reduce the peak magnitude of stress. Therefore, the maximum residual stress of VPPA-MIG hybrid welding is larger than that of single MIG welding, but the high stress area is narrower than that of single MIG welding, which is consistent with the research results in the literature [25]. Compared with conventional MIG welding, VPPA-MIG hybrid welding has the advantage of narrow high stress area, but has no obvious advantage in the peak magnitude of residual stress.

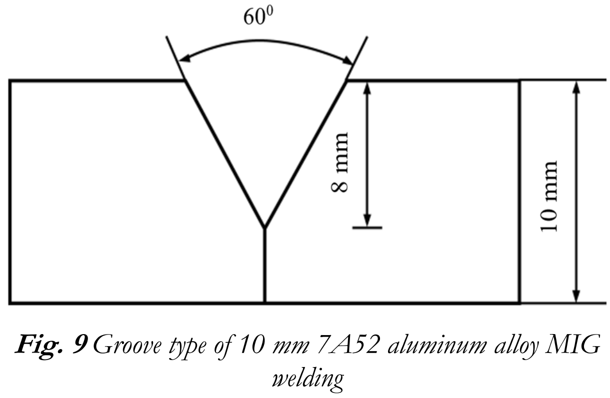


Fig. 9 *Groove type of 10 mm 7A52 aluminum alloy MIG welding*

4 Conclusions

In the process of 7A52 aluminum alloy VPPA-MIG hyrid welding, the effect of energy ratio on the distribution of residual stress was measured and analyzed by hole-drilling method. Important findings obtained are as follows:

(1) The energy ratio of VPPA arc increased about from 20% to 50%, the peak magnitude of transverse residual stress increases from 65.8 MPa to 98.3 MPa, and the peak magnitude of longitudinal residual stress increases from 186.7 MPa to 245.5 MPa. The peak magnitude of transverse residual stress and longitudinal residual stress increase with the increasing of the energy ratio of VPPA arc, and they are increased obviously when the energy ratio of VPPA arc is increased by about 10%.

(2) According to the residual stress distribution and its peak magnitude, the hybrid welding parameters of 7A52 aluminum alloy were optimized. When the energy ratio of VPPA arc between 35% and 40% are selected, not only the weld with satisfied macroscopic appearance can be obtained, but also the peak magnitude of residual stress is not being too high, which can avoid local stress concentration and improve the reliability of the hybrid welding joint. Compared with conventional MIG welding, VPPA-MIG hybrid welding has the advantage of narrow high stress area, but has no obvious advantage in the peak magnitude of residual stress.

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