MAG molten pool edge detection algorithm based on a fusion of dark channel prior dehazing and image enhancement*

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Metal active gas (MAG) welding is one of the widely applied welding techniques using argon and carbon dioxide as shielding gas. In response to the problem of welding halo and drag shadow during the image acquisition process of it, which makes it difficult to accurately extract the contour of the molten pool, this paper proposes a molten pool edge detection method that combines dark channel prior dehazing (DCPD) and improved single scale Retinex image enhancement algorithm. This method overcomes the problem of excessive edge noise in the original molten pool image and the difficulty in feature extraction caused by the dark part of the molten pool after DCPD processing. Through comparative experiments and ablation experiments, it has been shown that the algorithm proposed in this paper has significantly improved the enhancement effect and feature extraction effect, extracting accurate and complete molten pool contours.

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Metal active gas (MAG) welding, which uses a mixture of argon and carbon dioxide gas as the shielding gas, has the advantages of easy operation, low cost, and automation, making it suitable for various welding scenarios and becoming one of the widely used welding technologies. The features of the weld pool image contain important welding information. Accurately extracting the edge of the weld pool and further obtaining its size information is the main basis for welding image analysis. MAG welding is a process of intense physical and chemical changes, accompanied by noise interference such as high intensity halos and smoke generated by high temperature and heat, which exacerbates the difficulty of detecting the edge of the molten pool. Therefore, studying the edge extraction algorithm of MAG welding pool with strong anti-interference ability is of great significance for the research of welding quality.

Many scholars have conducted extensive research on anti-interference image processing to address the noise issue in the process of extracting molten pool parameters in welding. In order to obtain the size parameters of the 2219 aluminum alloy helium arc welding molten pool and analyze the characteristics of the molten pool, and reduce various noise signals such as splashing, smoke, oxide film noise, and interference images such as tungsten electrode reflection in the original molten pool image, XIAO et al[1] designed a series of image preprocessing methods. By combining image processing algorithms, including morphological reconstruction, XIAO accurately extracted a typical edge shape of the molten pool image and obtained the feature size of the molten pool width. In order to eliminate low-frequency background noise in the molten pool image acquisition system and obtain the contour, weld seam, arc shape of the molten pool, WEN et al[2] proposed a molten pool picture capture system that was on the basis of spatial filtering and Abbe image formation theory. WEN designed a high-pass spatial filter to eliminate the low-frequency background noise, thereby obtaining the contours of the molten pool, weld seam, and arc shapes. In contrast to the optical filter-based molten pool monitoring system, the problem of high radiation gradient in the molten pool area was solved by this method effectively and it can observe this molten pool more clearly. XU et al[3] proposed a morphological and dark channel defogging fusion algorithm for image preprocessing in order to filter out point like noise such as smoke and splash interference in the molten pool image, improve image clarity and contrast. This algorithm adopts the prior theory of dark channels and histogram equalization to filter out

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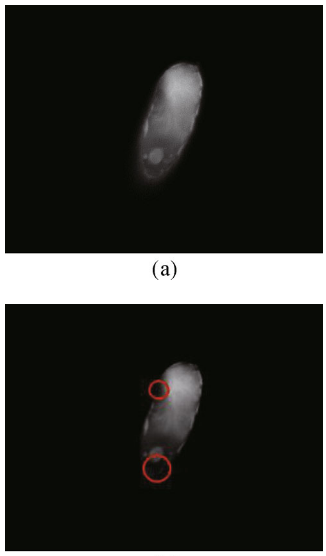
smoke and dust interference in the image, improving the richness of image information. The results show that the image texture changes processed by this algorithm are more regular. GAO et al[4] studied a dark channel prior anti-interference processing algorithm to reduce the interference of metal vapor and plasma during laser welding and achieve accurate welding quality identification, which used feature information extraction algorithms based on contour segmentation and OTSU threshold segmentation to extract features from welding images collected by the image acquisition system. The experimental results showed that this method can effectively eliminate the interference of metal vapor and plasma splashing on feature information.

At present, in the field of gas shielded metal arc welding, the methods used for extracting the edge of the molten pool are mainly based on grayscale features, such as grayscale threshold segmentation[5-8] and grayscale gradient[9]. These methods are susceptible to interference noise and have poor robustness, resulting in the inability to accurately extract the edge of the molten pool. And some of their edge detection methods[1,3,5,7,8] target a single-color molten pool with a simple extraction method, whereas in this paper, it is a molten pool with variable gray scale in MAG welding, and the edge detection method is more difficult, and the image processing process will become more complicated. ZHANG et al[10] proposed a prior dehazing method for underwater dark channels, which can remove some artifacts generated during this process, providing some insights for enhancing and removing noise in molten pool images. Some new methods[11] have been proposed to obtain molten pool information, which to some extent provides reference for the recognition and information extraction of molten pools.

In addition, the image enhancement-based denoising algorithm can largely enhance the image contrast to obtain a clear molten pool outline, but ignores the noise between the molten pool and the substrate in the image, making the molten pool boundary extraction inaccurate with a large error. And the image processing algorithm based on dark channel prior dehazing (DCPD) algorithm largely solves the noise between the edge of the molten pool and the substrate in the image, but the algorithm makes the dark part of the molten pool too dark and reduces the contrast with the substrate, resulting in too much deviation of the molten pool contour extraction, which cannot meet the expected effect. As shown in Fig.1, the right image is the original image, and the other one is the image after the DCPD processing (the red circle represents the difficulty in feature extraction due to the approximation between the dark part of the molten pool and the background). This is because the molten pool area is not a static color region, it is unevenly bright and dark, containing many gray uneven molten pool feature region, which will make the separate DCPD method and separate image enhancement methods cannot cope with the characteristics of the gray level of the changeable, so that the molten pool edge detection results are inaccurate. Therefore, the extraction of the molten pool contour must grasp the characteristics of the object, taking into account its grayscale characteristics, so as to obtain the ideal detection results. This paper proposes an edge detection method for MAG welding molten pool image processing method that integrates DCPD and image enhancement algorithms. Combining the advantages of both methods, an improved single scale Retinex (SSR) image enhancement algorithm combining gamma correction has been proposed. The experimental results show that this method improves the accuracy and completeness of the contour extraction of the molten pool significantly.



(a)

(b)

Fig.1 Comparison of images (a) before and (b) after DCPD

The overall algorithm flowchart of this paper is shown in Fig.2.

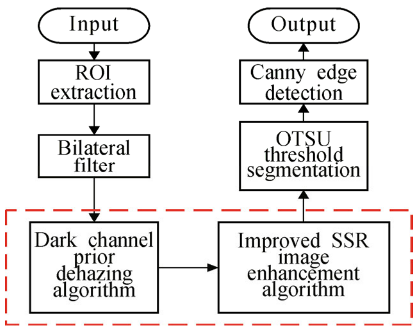


Fig.2 Flow chart of molten pool edge detection algorithm

The original size of the captured image is 640×480. After cropping and extracting the region of interest, the input size is 192×304. First, the Gaussian bilateral filtering[12] method is applied to smooth the noise with a window size of 5×5. The fusion algorithm of this paper is used for processing: first, the DCPD algorithm is performed to obtain the result image of the dark channel operation, and then the improved SSR image enhancement module is used to obtain the enhanced feature information, which can characterize the edge feature image of the molten pool accurately. Finally, the molten pool contour is extracted using threshold segmentation and Canny edge detection. The red dotted box shows the fusion algorithm in this paper.

The fog image degradation model is

$$I(x)=J(x)t(x)+A(1-t(x)), \quad (1)$$

where $I(x)$ is the fog image to be processed, $J(x)$ is the fog-free picture, A is the global atmospheric light, and $t(x)$ represents the dielectric transmittance. Eq.(1) expresses the meaning that the total light intensity $I(x)$ of the target scene into the imaging device is the superposition of the light intensity $J(x)t(x)$ after attenuation of the incident light and the light intensity $A(1-t(x))$ of the ambient light into the imaging device. The process of image dehazing is to obtain a haze-free image $J(x)$ from a haze image $I(x)$.

The DCPD algorithm was proposed by HE et al[13], who counted 5 000 fog-free images and found that there is always a channel with a very low gray-scale value in each RGB image, and the gray-scale value of this channel tends to almost 0. So there are the following conclusions for fog-free images as

$$J^{\text{dark}}(x)=\min_{y\in\Omega(x)}\left(\min_{c\in[R,G,B]}\left(J^c(y)\right)\right)\to 0, \quad (2)$$

where J^{dark} is the dark channel formulation, J^c represents the RGB three-channel pixel value, and $\Omega(x)$ is a square window centered at pixel x.

The above conclusion was obtained from natural fog-free images. For the MAG conditions in this article, the method is also applied to welding vapors, halos, and trailing shadows. This is because their effect on this picture is similar to that caused by natural fog.

Assume that the atmospheric light value A is known and the local $\Omega(x)$ transmittance is constant, denoted as $\tilde{t}(x)$. Firstly, divide both sides of Eq.(2) by $A^c, c\in$[R,G,B] at the same time, c is a certain color channel, and then make two minimum transformations on both sides at the same time, according to Eq.(1), the transmittance is obtained by collating as

$$\tilde{t}(x)=1-\min_{y\in\Omega(x)}\left(\min_c\left(\frac{I^c(y)}{A^c}\right)\right). \quad (3)$$

In practical situations, it is necessary to introduce a buffer factor ω, which is often taken as 0.95. This value is set to retain a certain degree of fog, because in real life, even if it is a sunny day, there will be some tiny particles in the air, when we look at objects in the distance, we are still able to feel the existence of the fog, and the availability of the fog can make the processing effect look more natural, so that people feel the presence of the depth of field, so it is necessary to retain a part of the fog. At this point, the transmittance is

$$t(x)=1-\omega\min_{y\in\Omega(x)}\left(\min_c\left(\frac{I^c(y)}{A^c}\right)\right). \quad (4)$$

By utilizing the correspondence between dark channels and foggy images, the position of the first 0.1% brightness pixels in the dark channel image is obtained to correspond to the higher brightness value in the corresponding position in the foggy image and thus selected as the global atmospheric light value A. Due to the small value of transmittance $t(x)$, it can lead to a larger value of $J(x)$. At this point, we set a lower limit value t_0 for transmittance, which is generally 0.1. When the value of t is less than t_0, the value of t is taken as t_0. Substitute the transmittance and global atmospheric light values we obtained into Eq.(2) to obtain the final fog-free image, as shown in

$$J(x)=\frac{I(x)-A}{\max\left(t(x),t_0\right)}+A. \quad (5)$$

The image processing algorithm based on DCPD algorithm largely solves the noise between the edge of the molten pool and the substrate in the image, but the algorithm makes the dark part of the molten pool too dark and reduces the contrast with the substrate, resulting in too much deviation of the molten pool contour extraction, which cannot meet the expected effect. So introduce an SSR image enhancement algorithm combined with gamma correction.

JOBSON et al[14] proposed the SSR algorithm based on the Retinex theory. The processing flow of the SSR algorithm is similar to the visual imaging process of the human eye. The principle can be represented by

$$S(x,y)=R(x,y)\cdot L(x,y), \quad (6)$$

where $S(x,y)$ represents the observed image, $R(x,y)$ is the reflection component of the object, and $L(x,y)$ represents the incident light component. The purpose of image enhancement is to estimate the illumination L from the original image S, thereby decomposing R and outputting it. Firstly, take the logarithm on both sides of Eq.(6) as

$$O(x,y)=\log R(x,y)=\log\frac{S(x,y)}{L(x,y)}. \quad (7)$$

Based on mathematical theory, the incident light component $L(x,y)$ cannot be directly calculated but instead is replaced by the convolution of $S(x,y)$ and a center surrounding function $F(x,y)$. The formula can be written as

$$O(x,y)=\log S(x,y)-\log[S(x,y)\otimes F(x,y)], \quad (8)$$

where $O(x,y)$ is the output result image, $\otimes$ is the convolution operator, and the center surrounding function $F(x,y)$ is generally realized by Gaussian function as

$$F(x,y)=K\mathrm{e}^{\frac{-(x^2+y^2)}{c^2}}, \quad (9)$$

where c is the Gaussian surround scale, and its value can easily affect the enhancement effect. When c is small, the details of the image can be maintained well, but the color may be distorted. When c is large, the details will be missing, but the color fidelity is high. As a constant, K must meet the following normalization conditions as

$$\iint F(x,y)\mathrm{d}x\mathrm{d}y = 1. \quad (10)$$

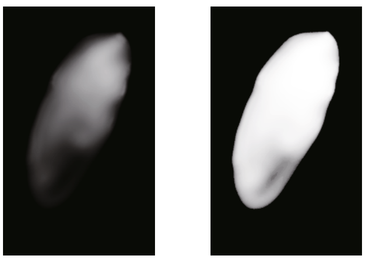
Before outputting the final result image, it is necessary to perform a linear stretching transformation on $R(x,y)$ and then output it. This process results in uneven edge processing of gray-scale images, and is accompanied by issues such as halo and excessive enhancement of weld pool edge details, which reduces the accuracy and completeness of weld pool edge extraction. To reduce the impact of this issue on the results, gamma correction is proposed for linear stretching transformation.

Gamma correction is a method of non-linear transformation of gray-scale, expressed as

$$V_{\text{out}} = A V_{\text{in}}^{\gamma}, \quad (11)$$

where V_{out} and V_{in} represent the output and input images, A is a constant, and γ is the gamma coefficient. In gamma correction, the γ value is usually 1. When γ is higher than 1, the highlight part of the picture becomes more prominent and the dark part is amplified. When γ is lower than 1, the highlight of the picture is amplified and the dark area is compressed. After multiple experiments, γ=2 was determined to be used for this algorithm to address the issue of excessive enhancement of the edge details of the molten pool after SSR enhancement.

The effect of image processing is shown in Fig.3. It can be seen from the figure that the enhancement algorithm effectively improves the dark features of the image, further laying a solid foundation for extracting the contour of the molten pool.



(a) (b)

Fig.3 Enhancement effects: (a) After dark channel processing; (b) After image enhancement

The molten pool image acquisition system is shown in Fig.4. The material used in this experiment is a size of 250 mm×120 mm×20 mm Q235 steel plate. In this image acquisition system, the welding gun and laser assisted system are fixed, and the welding material is driven by a movable platform. The movement of the platform is uniform linear motion, fixing the welding material on the mobile platform to avoid bumping and shaking, minimizing the shaking caused by welding during the welding process, and improving the stability to complete the welding test. The protective gas is 80% argon and 20% carbon dioxide at a flow rate of 20 L/min, which can effectively suppress welding porosity defects to ensure welding quality and greatly reduce atmospheric pollution. The welding machine model is PHOENIX 505, and the lens model is TAMRON MODEL 272E. The dataset comes from the molten pool images obtained by the image acquisition system in this experiment. The original image size is 640×480 pixels, and the cropped pixels are 192×304.

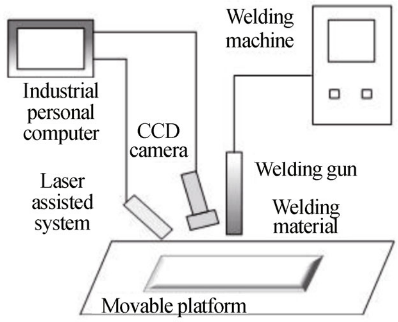
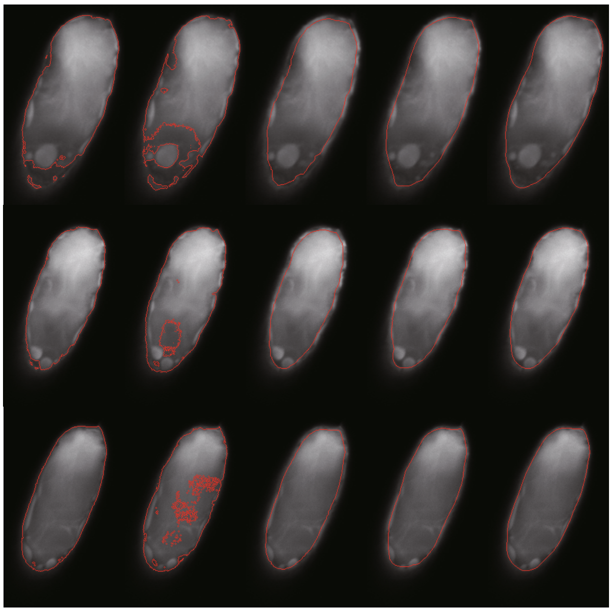


Fig.4 Molten pool image acquisition system

The above provides a detailed explanation of the fusion of DCPD and image enhancement for the molten pool edge detection algorithm. To verify the accuracy of the image processing algorithm in edge detection, this algorithm was used to test different MAG welding molten pool images and compare the test results with the results of traditional image processing algorithms and deep learning algorithms.

Fig.5 illustrates the effectiveness of classic image processing methods, such as the Canny algorithm, improved Clahe algorithm[15], Xiao's method[1] and the latest deep learning segmentation OCRnet algorithm[16] compared with the algorithm presented in this paper. To visually demonstrate the effectiveness of the algorithm, Canny edge detection was added to the third method[15]. Although the results in Fig.5(a), the column results are susceptible to the influence of low grayscale values and edge noise in the molten pool image, resulting in inaccurate or even incomplete contour extraction of the molten pool. In Fig.5(b), the improved Clahe image enhancement method combined with gamma correction can make the grayscale features of the image obvious and contrast enhanced, but it will make the dark parts of the image darker, ultimately leading to inaccurate extraction of the molten pool contour, significant errors, and significant localization in detecting weak edges. The results in Fig.5(c) show clear and complete contour features of the molten pool, but ignoring the edge features of the molten pool blurs the boundary between the edge of the molten pool and the background, making it difficult to obtain accurate contour edges that match the molten pool area. In Fig.5(d), the column of results can display the overall edge features of the molten pool, but there are still some deviations compared to the actual edge of the molten pool, which makes the detection of the molten pool edge inaccurate and susceptible to the influence of network training.



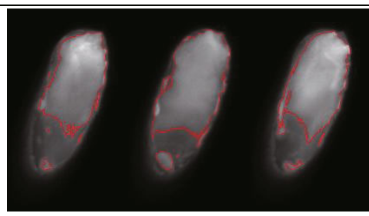
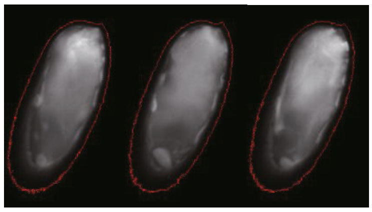
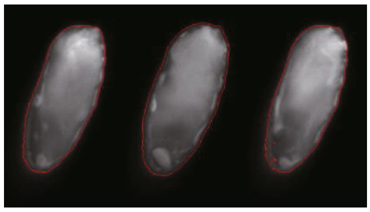
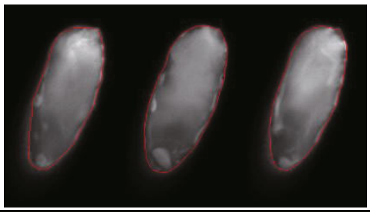
(a) Canny (b) Clahe (c) Xiao's (d) OCRnet (e) Ours

Fig.5 Comparison of experimental results of various algorithms

In summary, the limitations of the traditional algorithm in detecting the molten pool edge of MAG welding images are two: first, the welding halo and trailing smear cause the image gray-scale of the molten pool edge to be unevenly affected by edge detection; second, the molten pool edge is incomplete due to improper processing of the dark part of the melt pool during the image processing. And from Fig.5, we can see this paper compared to the traditional algorithm can well overcome the above two types of deficiencies, and Xiao's method can significantly improve the image of the molten pool edge feature information to achieve a good edge extraction effect, thus providing convenience for the subsequent calculation of the molten pool morphological parameters.

To further demonstrate the accuracy of the algorithm in extracting the edge contour of the molten pool, ablation experiments were conducted in this paper. Tab.1 shows the results of the entire ablation test process. " √ " represents the selection of the module. A is for DCPD, B is for improved SSR, and C is for OTSU. Line 1 adopts a DCPD algorithm to reduce the influence of the halo and trailing smear in the image, but this method will make the areas with the low gray level of the molten pool lower, and the fusion of the molten pool and the background makes it very difficult to extract the edge of the molten pool. Line 2 uses the SSR image enhancement method combined with gamma correction to extract the edges. Since the method is sensitive to gray scale, subtle light and shadow areas can be enhanced, which results in the area with halos at the edge of the molten pool and the molten pool becoming a whole connected area, making the results extremely inaccurate. The OTSU threshold method used in line 3 to extract the contour is relatively complete, but it cannot accurately identify the boundary between the molten pool edge and the background, resulting in inaccurate edge extraction results. The algorithm in this article combines the advantages of the above algorithms, effectively reducing the influence of halo in the edge detection process, and significantly improving the dark area of the molten pool, thereby extracting the edge of the molten pool that matches the real molten pool, and the contour of the molten pool is accurate and complete.

Tab.1 Results of the entire ablation test process

	A	B	C	Results
1	√	×	×	
2	×	√	×	
3	×	×	√	
4	√	√	√	

The previous paper is a qualitative analysis, in order to further show the advancement and superiority of this paper's method, we have done the following quantitative analysis. In this paper, the intersection over union (IoU) is used as an evaluation index to quantitatively judge the advantages and disadvantages of this method compared with other methods, and the IoU is calculated as the ratio of the intersection over union between the predicted region B and the real region B^{gt}. IoU is the ratio of the intersection and concatenation of predicted region and real region. The larger the value of the indicator, the better the result. The ideal situation is complete overlap, i.e., the ratio is 1. Fig.6 shows the schematic diagram of IoU, and the formula for calculating IoU is shown as

$$\mathrm{IoU}=\left|\frac{B\cap B^{gt}}{B\cup B^{gt}}\right|. \quad (12)$$

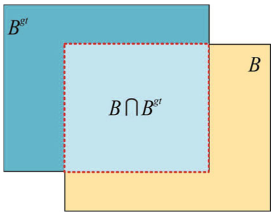


Fig.6 IoU diagram

The experimental results are shown in Tab.2. The Threshold Canny approach is to threshold the contour before using the Canny operator to extract the contour, otherwise it will lead to very poor edge detection. From the table, it is obvious that the IoU evaluation index of this paper's method is the highest, which strongly illustrates the superiority of this paper's method.

Tab.2 Comparative experimental results of different methods

Method	IoU
Thresholds Canny	0.894 4
Clahe	0.783 2
Xiao's	0.883 4
OCRnet	0.920 1
Ours	0.946 4

The experimental results of the quantitative analysis of the ablation experiment are shown in Tab.3. " √ " represents the selection of the module. The results can be visualized to show that the method of this paper is great. Although it is said that the result of the OTSU method is 0.927 5, it is far less effective than the result of the algorithm of this paper when combined with the results of the qualitative analysis above. This experimental result further illustrates the advancement and superiority of the method in this paper.

Tab.3 Experimental results of the quantitative analysis of the ablation experiment

	DCPD	Improved SSR	OTSU	IoU
1	√	×	×	0.854 7
2	×	√	×	0.613 4
3	×	×	√	0.927 5
4	√	√	√	0.946 4

We have established an MAG molten pool visual sensing system and collected high-quality welding pool images. A fusion algorithm of DCPD and SSR image enhancement is proposed for the extraction of molten pool contour in MAG molten pool images. The algorithm uses the SSR algorithm to improve the dark part of the image after the dark channel prior to processing and uses gamma correction to enhance the features of the weld pool edge extracted by the SSR algorithm, thereby obtaining accurate weld pool contour edges. After qualitative and quantitative analyses as well as comparative and ablation tests, the algorithm proposed in this paper can extract the accurate and complete contour of the MAG welding pool.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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