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A control system for uniform bead in fillet arc welding on tack welds

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Abstract

Positioning a workpiece accurately and preventing weld distortion, tack welding is often adopted before main welding in the construction of welded structures. However, this tack weld deteriorates the final weld bead profile, so that the grinding process is usually performed for a uniform weld bead profile. In this study, a control system for uniform weld bead is proposed for the fillet arc welding on tack welds. The system consists of GMA welding machine, torch manipulator, laser vision sensor for measuring the tack weld size and the database for optimal welding conditions. Experiments have been performed for constructing the database and for evaluating the control capability of the system. It has been shown that the system has the capability to smooth the bead at the high level of quality.

Keywords: GMA welding; Tack weld; Fillet welding; Uniform bead shape; Laser vision sensor

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1. Introduction

In gas metal arc (GMA) welding, the weld size is one of the most important factors determining the strength of a welded structures. The target size of the weld bead is determined according to the workpiece thickness, weld length, weld joint type etc. In addition, the uniformity of the bead size is also important from the standpoint of appearance as well as strength. In the construction of welded heavy structures, tack welding is often executed for positioning the workpiece accurately and preventing weld distortion before the main welding. However, this tack weld deteriorates the final weld bead profile, so that the grinding process is usually adopted for the uniform weld bead profile [1, 2].

In this study, a control system for uniform weld bead is proposed for the fillet arc welding on tack welds. The system consists of GMA welding machine, torch manipulator, laser vision sensor for measuring the tack weld size and a database for optimal welding conditions. The database for welding conditions was constructed by using response surface methodology. The experimental method was used for the response surface analysis in which the leg length and the reinforcement height of the weld bead were chosen as the quality variables of the weld bead profile [3]. The overall desirability function, which combined desirability functions for the two quality variables, was used as the objective function for getting the optimal welding condition [4, 5].

A laser vision sensor was designed and constructed for on-line measuring the tack weld size, which was determined from the image processing of Hough transform. The vision sensor system consists of a CCD camera, a diode laser system with a cylindrical lens, and a band-pass-filter to overcome the degrading of image due to spatters and/or arc light [6, 7]. Measuring the tack weld size by the vision sensor, the optimal welding condition for getting the final target bead size is determined from the database. At every sampling time, the control system executes the selected welding condition during welding process. A

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series of experiments has been performed for evaluating the control capability of the system.

2. Optimal welding conditions

The weld size produced in the GMA welding process is determined by process variables such as arc voltage, welding current, welding speed and so on. It is thus important to select an optimal welding condition for getting the target weld size. The optimal welding conditions according to the tack weld size were obtained by using the response surface methodology.

2.1 Experimental design and modeling

The response surface methodology (RSM) is comprised of experimental design, statistical modeling, and optimization. In this study, the RSM was used to determine the welding conditions which would optimize the weld bead size [3]. The leg length and reinforcement height were to be set as the output variables because those are the bases of bead size (Fig. 1). As a target weld size in this study, the leg length and reinforcement height are selected as 6 mm and 0 mm, respectively. The welding speed (x_1), welding current (x_2), and voltage (x_3) were selected as the input variables which play an important role in formation of weld bead [2]. By using these input variables, the approximated models were assumed as the following second-order regression models:

$$L = \alpha_0 + \sum_{i=1}^{k} \alpha_i x_i + \sum_{i \le j}^{k} \alpha_{ij} x_i x_j + \varepsilon_L \tag{1a}$$

$$H = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i \le j}^{k} \beta_{ij} x_i x_j + \varepsilon_H \tag{1b}$$

where L is the leg length, H is reinforcement height, α 's and β 's are unknown coefficients. The unknown coefficients can be estimated through the method of least squares by using experimental data. ε_L and ε_H are random errors. In order to derive the second-order regression model, the central composite design (CCD) was used in this study as an experimental design. The experimental conditions in the Table 1 and 2 were implemented. And the experimental design and the results for the case of no tack weld are as shown in Table 3. Thus the following regression models could be derived by using the experimental results:

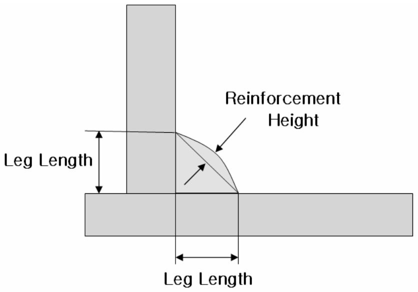


Fig. 1. Nomenclatures for the fillet weld size.

Table 1. Factors and level for experimental design.

	Factors	Level		
		-1	0	1
x_1	Welding speed [cm/min]	58	52	46
x_2	Welding current [A]	280	300	320
x_3	Welding voltage [V]	32	34	36

Table 2. Fixed welding conditions.

Tip-to-base metal distance (mm)	20
Torch angle (°)	45
CO_2 Gas flow (ℓ /min)	18
Welding wire diameter (mm)	1.2

Table 3. Central composite design and experimental results.

Run	Coded units			Bead sizes	
	x_1	x_2	x_3	L	H
1	-1	-1	-1	5.2	0.42
2	1	-1	-1	5.55	1.08
3	-1	1	-1	5.2	2.32
4	1	1	-1	5.6	3.04
5	-1	-1	1	5.55	0.18
6	1	-1	1	6.35	0.31
7	-1	1	1	5.6	1.04
8	1	1	1	6.6	0.83
9	-1	0	0	5.6	0.54
10	1	0	0	6	0.86
11	0	-1	0	5.9	0.43
12	0	1	0	5.7	1.37
13	0	0	-1	5.6	1.14
14	0	0	1	6.05	0.32
15	0	0	0	5.9	0.73
16	0	0	0	5.9	0.63
17	0	0	0	5.85	0.76

$$\begin{aligned}\hat{L} &= 5.873 + 0.295x_1 + 0.015x_2 + 0.3x_3 \\ &\quad - 0.064x_1^2 - 0.064x_2^2 - 0.039x_3^2 \\ &\quad + 0.031x_1x_2 + 0.131x_1x_3 + 0.031x_2x_3\end{aligned} \tag{2a}$$

$$\begin{aligned}\hat{H} &= 0.653 + 0.161x_1 + 0.619x_2 - 0.532x_3 \\ &\quad + 0.086x_1^2 + 0.286x_2^2 + 0.118x_3^2 \\ &\quad - 0.035x_1x_2 - 0.18x_1x_3 - 0.31x_2x_3\end{aligned} \tag{2b}$$

2.2 Determination of optimal welding conditions

The regression (2-a) and (2-b) are the equations that express the bead size depending on the variables of x_1, x_2, and x_3. Therefore, it is necessary to select the optimal values of the input variables that would satisfy both the leg length and reinforcement height simultaneously. The desirability function approach is an effective method in finding a set of input variables to optimize the multiple responses [4, 5]. This method is comprised of the transformation of each response into a desirability function, each desirability function into an overall desirability function, and optimization of the overall desirability function. In this study, the following desirability functions for the leg length and reinforcement height were used, respectively.

$$d(\hat{L}_{(x)}) = \begin{cases} 0, & \hat{L} \langle 5.5 \\ \dfrac{\hat{L} - 5.5}{6 - 5.5}, & 5.5 \le \hat{L} \le 6 \\ \dfrac{\hat{L} - 6.5}{6 - 6.5}, & 6 \le \hat{L} \le 6.5 \\ 0, & \hat{L} \rangle 6.5 \end{cases} \tag{3a}$$

$$d(\hat{H}_{(x)}) = \begin{cases} 0, & \hat{H} \langle -0.1 \\ \dfrac{\hat{H} - (-0.1)}{0 - (-0.1)}, & -0.1 \le \hat{H} \le 0 \\ \dfrac{\hat{H} - 1.0}{0 - 1.0}, & 0 \le \hat{H} \le 1.0 \\ 0, & \hat{H} \rangle 1.0 \end{cases} \tag{3b}$$

The overall desirability function as the geometric mean of the individual desirabilities was defined and used as follows:

$$D_{(x)} = \left\{ d(\hat{L}_{(x)}) \cdot d(\hat{H}_{(x)}) \right\}^{\frac{1}{2}} \tag{4}$$

Fig. 2 shows the surface of overall desirability according to welding current and voltage at a welding speed of 50.74 cm/min for the case of no tack weld.

Table 4. Optimal welding conditions according to the tack weld size.

Tack weld size	$d(\hat{L}_{(x)})$	$d(\hat{H}_{(x)})$	$D_{(x)}$	Coded variables			Natural variables		
				x_1	x_2	x_3	x_1	x_2	x_3
None	0.999	0.841	0.917	-0.21	-0.56	1.0	50.74	288.8	36.0
2 mm	0.999	0.688	0.829	0.66	-1.0	0.63	55.96	260.0	34.26
2.5 mm	0.997	0.515	0.717	1.0	-0.69	0.39	58.0	256.2	33.78
3 mm	0.999	0.554	0.744	0.09	-0.08	1.0	52.54	258.4	34.0

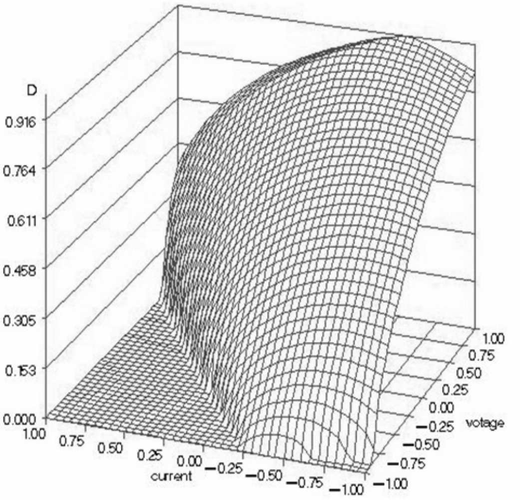


Fig. 2. Overall desirability according to welding current and voltage at welding speed of 50.74 cm/min.

In the region of interest, the optimal input variables were determined, which results in the maximum overall desirability. These processes were repeated for the cases of various tack weld size. The optimal welding conditions according to the tack weld size could be obtained as shown in Table 4. In the study, these selected welding conditions were adopted as the database in the control system. The interpolated values are calculated and implemented as the optimal condition for the corresponding tack weld size.

3. Control system

The objective of the control system is maintaining the weld bead smooth in spite of welding on a varying tack weld size. The overall control scheme is as shown in Fig. 3. On the basis of measuring the tack weld size by using the preview vision sensor, the system controller determines the proper welding condition for the target weld size from the database and

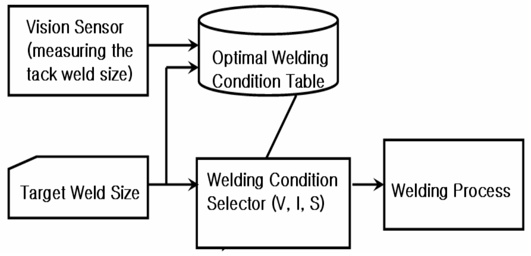


Fig. 3. Schematic diagram of the overall control system.

implements the welding process with the selected conditions. The detailed explanations for the vision sensor and the control scheme are as follows.

3.1 Laser vision sensor

A preview-sensing visual system is constructed for measuring the tack weld size. The laser vision sensor consists of a CCD camera, a diode laser system with a cylindrical lens, and a band-pass-filter to overcome the degrading of image due to spatters and/or arc light. The diode laser as a source of structured light has its wavelength of 690.4 nm and power of 3 mW. After the consistency in wavelength of the laser was measured, an optical band pass filter was selected, through which the light of wavelength range 690.4±5 nm can pass. The focusing length, the distance from the camera lens to object, was set to 96 mm in order to make the system have resolution of 0.02 mm in the cross direction of weld line (i.e., horizontal direction in the image). The angle of illuminating direction of the laser stripe from vertical axis, which is generally set to 20-40° [6, 7], affects the resolution in the vertical direction and the size of sensor. Considering these effects, the angle of illuminating direction of the laser stripe was set to 30° in this sensor system. The illuminated laser stripe on the surface of object has a length of 40 mm and width of 0.5 mm. The nominal look-ahead distance, the distance from weld torch to laser stripe in the direction of weld line, was set to 67.8 mm. The configuration of the laser vision sensor is as shown in Fig. 4 and Fig. 5.

3.2 Image processing

There are two steps in the image processing for measuring the weld size of fillet joint. First, the structured light, which is the image of the laser stripe on the workpiece, has to be extracted from the background of camera image. Secondly, the feature positions, for example, the weld groove point and the wetting point of weld bead, are determined.

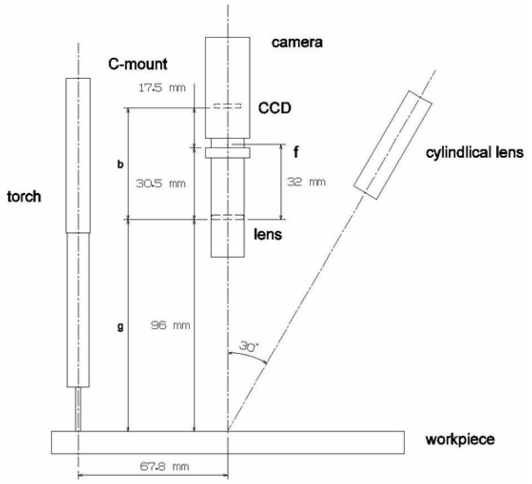


Fig. 4. Configuration of the laser vision sensor.

Fig. 5. Photograph of the laser vision sensor.

A vertical 21-pixel (Lt) mask window was used for extracting the laser stripe. (Fig. 6) The window moves from top to bottom along the first column on the image and the sum of gray level of the window is saved. The sum of gray level of the n^{th} window (M_n) is obtained by using the equation (5-a) or (5-b) as its recursive form.

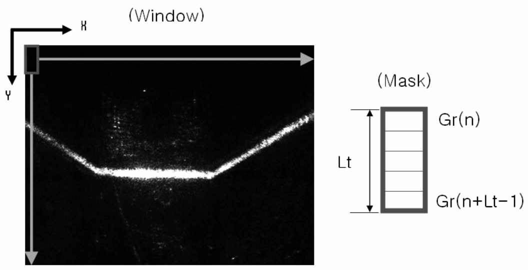
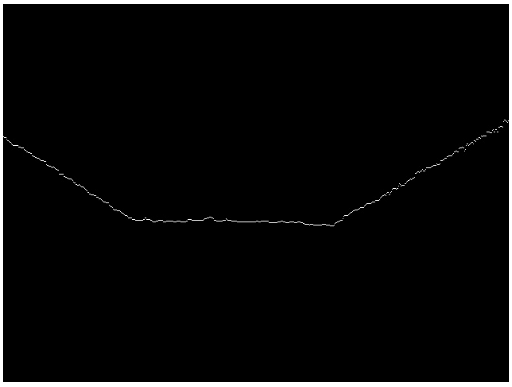
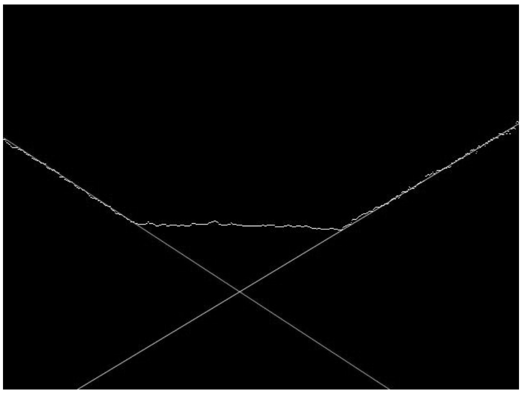


Fig. 6. Extracting method of laser stripe from the raw image.



(a) Image after thinning



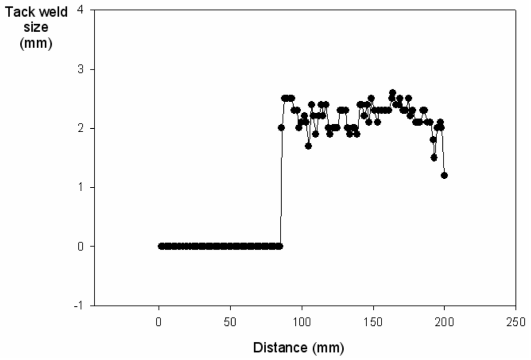
(b) Straight line extracted by Hough transform

Fig. 7. Result of image processing.

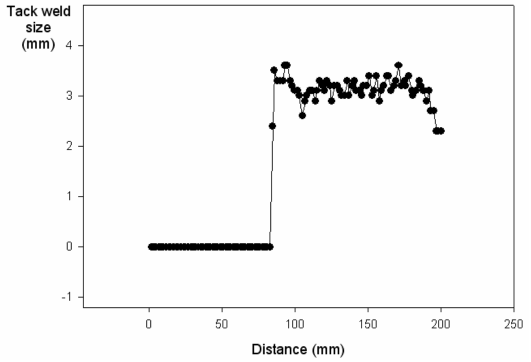
$$M_n = Gr(n) + Gr(n+1) + \cdots + Gr(n+Lt-1) \tag{5a}$$

$$M_n = M_{n-1} - Gr(n-1) + Gr(n+Lt-1) \tag{5b}$$

The window which has the maximum gray level sum is chosen, and then the mid-position pixel of the window is set to a point of structured light at the column. This process repeats to the last column. Fig. 7(a) shows the image after this thinning process.



(a) Nominal tack weld size of 2 mm



(b) Nominal tack weld size of 3 mm

Fig. 8. Measured tack weld size by laser vision sensor.

Next, Hough transform method is carried out to extract straight lines that express laser stripe [8, 9]. Every pixel datum has its ρ and θ value with respect to a fixed point as shown in Eq. (6); the center point of the full image was assigned as the fixed point in this study. Determining the characteristic values of ρ and θ, then the gradient, 'a' and y-intercept, 'b'in the Eq. (7) can be obtained. These are the straight lines extracted from the thinned image of the structured light.

$$\rho = x \cdot \cos\theta + y \cdot \sin\theta \tag{6}$$

$$y = ax + b \tag{7}$$

After the lines are extracted, weld joint position and edge points are determined by intersecting the lines. (Fig. 7(b)) Finally, the bead size of the tack weld, especially the leg length, is determined.

3.3 Control scheme

An accurate measurement of the tack weld size permits determining the optimal welding condition for getting the final target bead size. A selected welding condition at the measuring location is to be put in the memory. When the torch reaches the location, the saved welding condition is picked from the memory and executed. This control scheme is presented in Fig. 3. The measured bead size is averaged at every sensing time for smoothing the control input. The system performs this control action consecutively with 0.17 sec of sampling time.

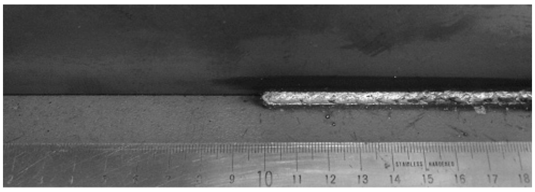
4. Experimental results and discussion

4.1 Measuring of tack weld size

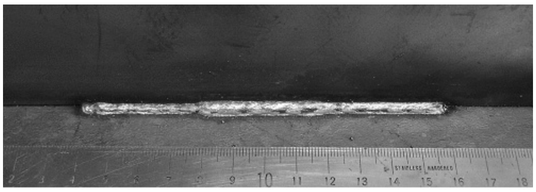
Various tack weld specimens were made by using the GMA welding process. Generally, the weld size is not perfectly even through the whole weld length. Thus two specimens which have an average size of 2 and 3 mm were chosen and measured, and the specimens were named as its nominal tack weld size. The measured tack weld sizes are as shown in Fig. 8, where the average values of the measured ones coincide well with its nominal size, respectively. Since the fluctuation of the measured values may badly affect the control action, the moving averaged values are adopted in the control system. The smaller values of the measured data at the end zone of weld line are due to the small size of the real bead at the crater area. Since the optimal weld conditions were constructed on the basis of the nominal tack weld size, the capability of the laser vision sensor developed is considered as acceptable for the weld bead control system.

4.2 Bead smoothing by the control system

By using the proposed control system, a series of experiments were performed for the various tack weld size specimens as shown in Fig. 9. In order to confirm the control action, uncontrolled welding was also done. In Fig. 10, a controlled bead shape was compared with uncontrolled one, in which the main welding was done over the 2.5 mm tack welds. In the case of no-control action, since a constant welding condition was executed, the final bead shows bigger size and even overlapping on the tack weld location. However, in the controlled one, the final weld bead is maintained with uniform profile in the whole range of

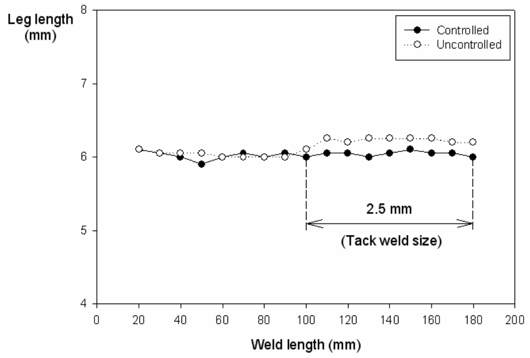


(a) 2.5 mm tack weld specimen

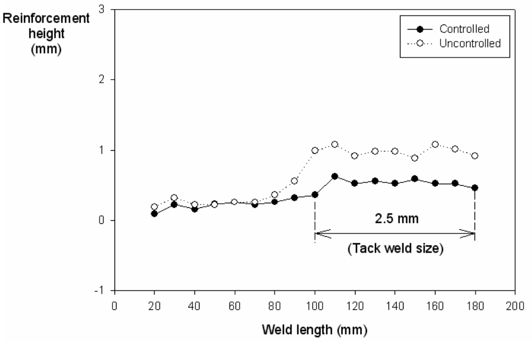


(b) 2 mm - 3 mm - 2.5 mm tack weld specimen

Fig. 9. Specimens for welding experiments

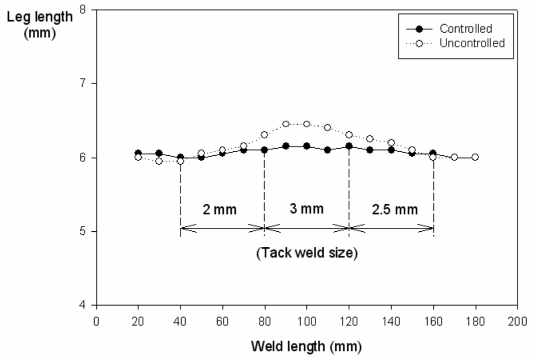


(a) Leg length

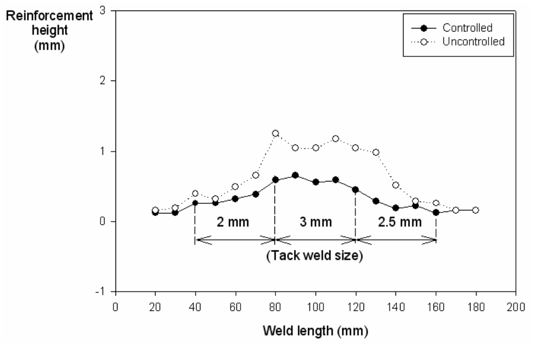


(b) Reinforcement height

Fig. 10. Comparison of bead size over the constant tack weld size of 2.5 mm



(a) Leg length



(b) Reinforcement height

Fig. 11. Comparison of bead size over the varying tack weld size(2, 3, 2.5 mm).

weld line. In Fig. 11, main welding was done over the varying tack weld size from 2 mm to 3 mm, and to 2.5 mm consecutively. Even over the varying tack weld size, the control system formed smoother final bead than the uncontrolled one. In the case of the controlled weld bead, the variation of leg length is within 0.3 mm and the variation of reinforcement is within 0.5 mm. This uniformity of the weld bead can belong in the high level of acceptable quality. Thus, it was revealed that a uniform final weld bead over the tack weld can be obtained by a control action such as that of the proposed system.

5. Conclusions

In this study, a control system for uniform weld bead was proposed for the fillet arc welding on the tack welds. The database for the optimal welding condition was constructed by using an experimental method which uses the response surface analysis. A laser vision sensor was designed and constructed for on-line measuring the tack weld size by using an optical triangulation principle, and the leg length of the tack weld was determined from the image processing of Hough transform. Experiments have shown that the system can precisely measure the tack weld size enough for the control system. And the proposed control system has shown the capability to produce a uniform weld bead at a high level of acceptable quality.

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