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Automatic measurement method for the size of large forgings based on scattering on rough surface

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Yu-Cun Zhang[1], *Cheng Luo*[1] ✉, *Xian-Bin Fu*[2], *Yi-Ming Chen*[1]

[1]*School of Electrical Engineering, Yanshan University, Qinhuangdao City, Hebei Province, People's Republic of China*
[2]*Hebei University of Environmental Engineering, Qinhuangdao City, Hebei Province, People's Republic of China*
✉ *E-mail: luocheng003@stumail.ysu.edu.cn*

Abstract: The size measurement of large hot forgings plays an important role during the process of production. In order to realise the size measurement of large forgings in thermal state, an automatic size measurement method for large forgings based on the scattering of rough surface is proposed in this study. In the method, the theory of random facets is applied to research the characteristic of laser scattering on the surface of hot forgings. The model of laser scattering on the random rough surface of cylinder is built. According to the model, the edges of forgings can be detected and the size of forgings can be got. First, the charge coupled device (CCD) camera and the green laser are driven by the motor to move on the guide rail. The real-time images of forgings are captured by CCD camera and the positional information of laser is acquired by pulse coder. Then according to the change of the intensity of the scattered light, whether the laser line is on the edge of forgings is decided. Second, the positional information of two edges is got by pulse coder and the size of forgings is figured out by the positional information. Finally, the feasibility of the method is verified by the experiment of size measurement.

1 Introduction

Large forgings are the important basic parts of major equipment manufacturing industry and major engineering construction, as well as the premise of developing advanced equipment manufacturing industry. The improvement of manufacturing technology of large forgings has become an important reflection of developmental level of a nation's national defence [1, 2]. However, in the process of production, forgings are likely to become waste product because of the inaccuracy of measurement, which undoubtedly results in huge waste of resources. Therefore, the size measurement of forgings plays an important role in the process of production [3]. The improvement of measuring accuracy for large forgings is of great significance to energy conservation and emission reduction.

There are generally two ways for measuring size [4], contact and non-contact approaches. Because of its low measurement accuracy and bad working condition [5, 6], the contact approach is rarely used. Over the past two decades, 3D measurement has become a new technique in the accurate measurement field. Golnabi [7] designed a laser scanning system based on a synchronised scanning geometry. The system offered a good reproducibility and resulted agrees well with the theory. Lichti and Licht presented advances in terrestrial scanner system [8]. The error model they proposed achieved that results from self-calibration and accuracy assessment experiment are, respectively, up to 80 and 36%. In the research of Gonzalez-Jorge *et al.* [9], photogrammetry and laser scanner technology were applied to length measurements in car testing laboratories. The metrological suitability to obtain the geometrical parameters in car testing laboratories can meet the standard. Microsoft Kinect sensor as a measurement device is widely used [10, 11]. It has advantages of low price and high accuracy. In the field of forgings measurement, scholars at home and abroad have done lots of research on the size measurement for forgings in laser based non-contact approach recent years [12, 13]. Based on laser scanning, the Hot-Eye coordinate measuring system designed by OG Technologies of USA [14, 15] had achieved the measurement of small hot forgings. The LaCam measuring system for forgings developed by FERROTRON Technologies of Germany [16] had a similar operating principle. Although these two systems have a high precision, how to extract feature information of forgings from huge amount of point cloud data still need further research when measuring large forgings. In order to increase the measurement range and satisfy the need of the measurement for large forgings, measuring method for large hot forgings based on structured light was proposed. Sandro *et al.* [17] achieved the matching of structured light by measuring the three-dimensional coordinate of datum point. According to the relevance between the datum point and the point cloud data, the whole data of forgings' surface were captured. Zhang *et al.* [18, 19] proposed a structured light vision measuring system. By processing the images of structured light got during the process of scan, the size of forgings can be got. A structured light measurement model was established by Liu *et al.* [20] based on the theory of parabola piecewise fitting. The piecewise fitting was used to detect the edge of measured object and then the large-scale measurement was achieved. Jia *et al.* [21–23] put forward a method based on structured light and dual charge coupled device (CCD). Sub-pixel extraction algorithm and structure light binary code are applied in the method to achieve the diameter measurement for cylindrical forgings. A stereo vision measuring method based on structured light was proposed by Liu [24]. In this method, digital filter technology, temporal phase unwrapping structured light technology and multi-view auto registration techniques are applied to achieved the measurement of large hot forgings. Combining computer vision, structured light, fringe projection, phase shifting and digital optical filter, a 3D measuring method is proposed for non-contact measurement of hot forging parts by Zhao *et al.* [25]. When these methods are applied to practice, forgings need to be scanned to acquire the information from light stripes. The 3D information of forgings' surface can be acquired through the parameter of the system. However, the bigger the forging is, the more time is needed to scan the light stripes and to process the point cloud data. It is bad for the measurement of forgings that has a higher request for time. What's more, the calibration of stereo vision measurement system becomes very hard in the environment of high temperature. Therefore, it needs further research that how to guarantee the real-time performance. So does the problem that the parameter calibration is needed in a complex environment.

In this paper, an automatic size measurement method for large forgings based on the scattering on rough surface is proposed. Based on the method, a size measurement system is built. The system detects the edges of forgings through the change of scattering light on forgings when the laser scanning the forging. The positional information of laser is got by pulse coder. Hence the positional information of edges can be got. Then the automatic measurement is achieved by the system. Due to the adoption of pulse coder, the positional information can be read and displayed on PC in real-time, which makes the system can do the measurement without calibration. The whole measurement process can also be monitored by PC.

2 Measurement system for large forgings

The size measurement system mainly consists of green laser, CCD camera, detector, guide rail and the servo control system. The schematic diagram of measurement system is shown in Fig. 1. In this system, the green laser, the CCD camera and the detector are fixed on the platform that can slide on the guide rail along the direction of the axis of forgings. When the laser line in the different position, the intensity of the scattered light the laser line produced is also different. According to the change of the intensity of the scattered light, whether the laser line is on the edges of forgings can be decided. When the system detects that the laser line is on the one edge of forgings, the positional information will be got. So does the other edge. The size of forgings is the distance of two positions. The model of the line laser adopted in this paper is MGL-III. The wavelength of the laser is 532 nm. The aperture angle is 30°. The model of the industrial CCD camera is MV-VE078SM/SC, maximum resolution is 1024 × 768, the size of a pixel on the CCD array is 4.65 × 4.65 μm, and frame rate is 30 fps. The model of detector is XYI-III, its error is less than 4%. The model of guide rail is BGXS45BE, the guide rail is as long as 4500 mm, walking error is less than 40 μm. In order to protect the devices, the CCD camera, the detector and the laser are fixed in a box which can slide on the guide rail. Its dimension is 350 × 300 × 350 mm. The box and the guide rail are shown in Fig. 2. The model of servo motor is MR-J2S-1 0A/B. A PC is used to compute, control and display in the system. The model of PC is DELL OptiPlex 9020 with an Intel Core i5-4590 CPU and 4 GB RAM. The PC is shown in Fig. 3. In the system, the program is written in C# because of its simpleness, convenience and stabilisation.

3 Principle of measurement

3.1 Model of scattering on rough cylindrical surface

There is oxide skin on the surface of forgings. Compared with the wavelength of laser, the surface of forgings can be regard as rough surface. Hence the surface of forgings can be divided into small rough surface elements. The whole scattering light intensity is the sum of all the scattering light intensity on every small surface element.

In Fig. 4, the radius of cylindrical forging is R. The distance between light source S and the forging is L_1. The angle between the axis of S and the positive direction of z-axis is θ_s. The power of laser is J. The divergence angle of the laser is θ. The distance between detector and the forging is L_2. The pitch angle of detector is γ and the azimuth is φ.

Apparently, only half of the forging can be irradiated by the laser. The cylindrical surface is partitioned into small cylindrical surface elements along the direction of the axis of the forging. α is used to describe the polar coordinates of any element. The range of α is from $-\pi/2$ to $\pi/2$. The cylindrical surface is divided into I parts. I is even number. Hence the angle of every part is

$$\Delta\alpha = \frac{\pi}{I} \tag{1}$$

The angular coordinate of the ith surface element is

$$\alpha_i = i\Delta\alpha \tag{2}$$

where $i = -I/2, -I/2+1, \ldots, 0, \ldots I/2-1, I/2$.

The length of the projection of laser beam on every element is

$$l_i = \frac{\sqrt{L_1^2\theta^2 - 4R^2\sin^2\alpha_i}}{\cos\theta_s} \tag{3}$$

The area of every element is

$$\Delta S_i = R\Delta\alpha l_i = \frac{\pi R\sqrt{L_1^2\theta^2 - 4R^2\sin^2\alpha_i}}{I\cos\theta_s} \tag{4}$$

The more the I is, the smaller the surface elements are. Hence every small cylindrical surface element can be regarded as a small rough plane. In order to calculate the distribution of scattering power on every small plane, coordinate systems are built for every small plane. With the increase of angular coordinate, the pitch angle and the azimuth generated by the detector and every small plane will change. So will the incident angle of every small plane.

The incident angle of the ith small plane is:

$$\theta_{si} = \arccos(\cos\theta_s\cos\alpha_i) \tag{5}$$

The angle of pitch generated by the detector and the ith small plane is

$$\sigma_i = \arccos(\sin\gamma\sin\varphi\sin\alpha_i + \cos\gamma\cos\alpha_i) \tag{6}$$

The included angle between the projection of axis of detector on xoz plane and the positive direction of z-axis is $\theta_{x,i}$. The included angel between the projection of axis of detector on yoz plane and the positive direction of z-axis is $\theta_{y,i}$.

$$\theta_{x,i} = \arcsin\left(\frac{\sin\sigma_i\cos\varphi}{\sqrt{1-\sin^2\sigma_i\sin^2\varphi}}\right) \tag{7}$$

$$\theta_{y,i} = \arcsin\left(\frac{\sin\sigma_i\sin\varphi}{\sqrt{1-\sin^2\sigma_i\sin^2\varphi}}\right) \tag{8}$$

Therefore, the probability of the detector receiving the scattered light from the ith small plane is

$$P_i(\theta_{x,i}, \theta_{y,i}, k) = \frac{1}{2\pi k^2} \times \exp\left\{-\frac{\tan^2[(\theta_{si}-\theta_{x,i})/2] + \tan^2[(\alpha_i-\theta_{y,i})/2]}{2k^2}\right\} \tag{9}$$

where k is the root-mean-square (RMS) slope of the forging.

According to the power distribution of scattered light on rough surface, the scattering power received by the detector from the ith

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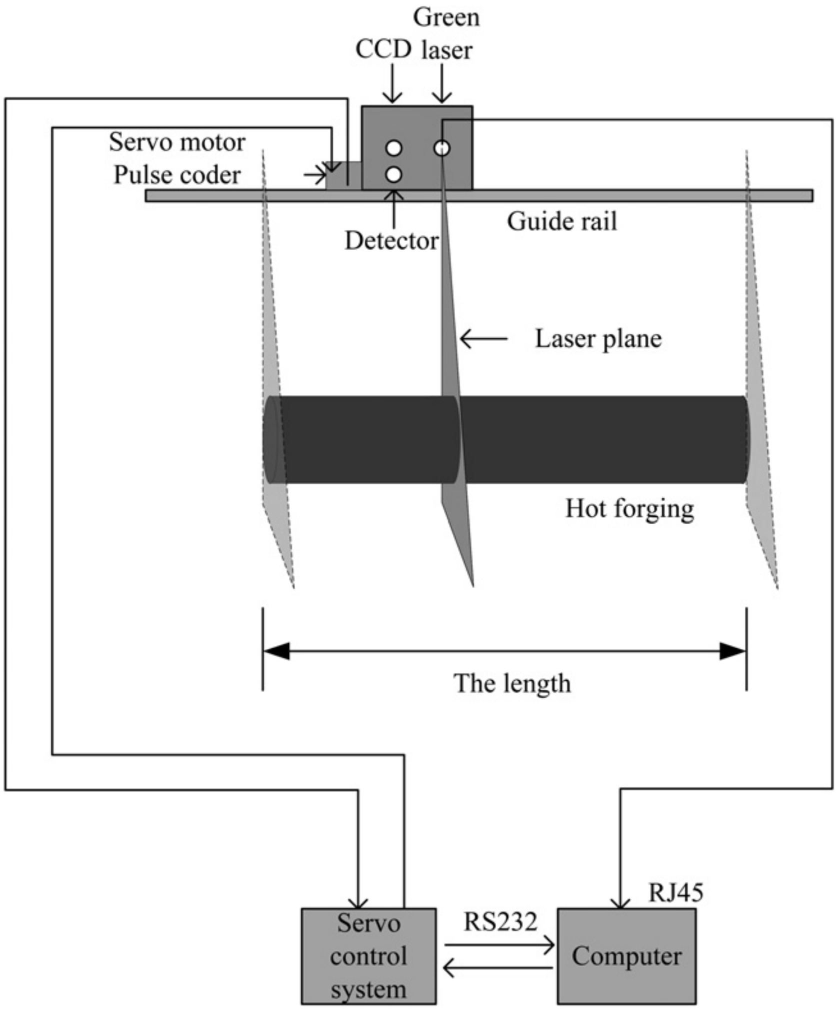

Fig. 1 *Schematic diagram of forgings dimension measurement system*

small plane is

$$J_i = \eta\mu \frac{J \Delta S_i \cos\theta_{di}}{\pi L_1^2 \theta^2 \xi(k)} \rho P_i(\theta_{x,i}, \theta_{y,i}, k) \times \left(\cos\frac{\theta_{si} - \theta_{x,i}}{2} \cos\frac{\alpha_i - \theta_{y,i}}{2} \right)^{-2} \tag{10}$$

where η is the receiving efficiency of detector, μ is the power transmittance of atmosphere, ρ is the mean reflectance of laser on the surface of forging, $\xi(k) \simeq (1 + 2k)^{-1/2}$ is the flattening factor of small rough plane.

When $\left|(\theta_{si} - \theta_{x,i})/2\right| \geq (\pi/2)$ or $\left|(\alpha_i - \theta_{y,i})/2\right| \geq (\pi/2)$, $J_i = 0$.

Fig. 2 *Box and the guide rail*

Fig. 3 *PC in the system*

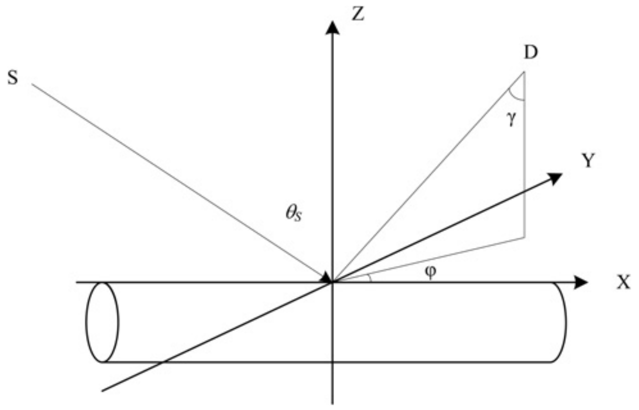

Fig. 4 *Schematic diagram of cylindrical surface scattering*

The whole scattering power received by detector is the sum of the scattering power on every small plane.

$$J_0 = \sum_{i=-I/2}^{I/2} J_i \tag{11}$$

Substituting k, γ, φ etc. into (10) and (11), the scattering power can be figured out.

3.2 Model of scattering on rough cylindrical surface

In Section 3.1, the scattering intensity of laser irradiating on forgings completely can be figured out. The change of scattering intensity when laser on the edge of forgings need to be researched in order to measure the size of forgings accurately. The situation that laser scan the forging is shown as Fig. 5. In the figure, x_l is the horizontal coordinate of the centre of the laser beam, d is the width of laser beam, x_1 and x_2 are the horizontal coordinates of the edges of the forging, respectively. The scanning process has four kinds of situations:

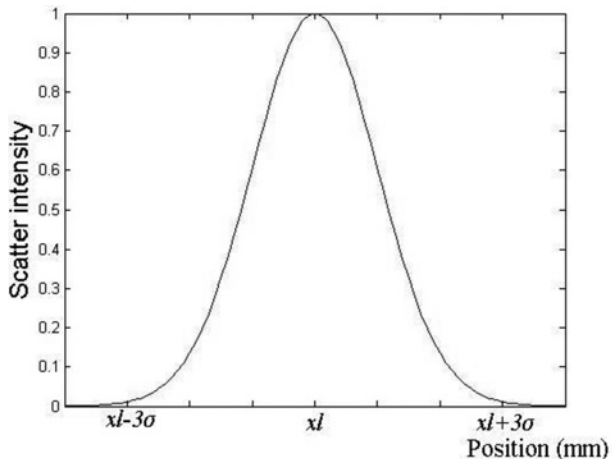

Fig. 6 *Distribution of scattering intensity*

(i) The laser beam is out of the forging. ($x_l < x_1 - d/2$ or $x_l > x_2 + d/2$).
(ii) The laser beam is on the forging. ($x_1 + d/2 < x_l < x_2 - d/2$).
(iii) The laser beam is on the edges of the forging and the centre of laser beam is on the forging. ($x_2 - d/2 \le x_l \le x_2$ or $x_1 \le x_l \le x_1 + d/2$).
(iv) The laser beam is on the edges of the forging and the centre of laser beam is out of the forging. ($x_2 < x_l < x_2 + d/2$ or $x_1 - d/2 < x_l < x_1$).

In the four kinds of situations, the scattering power received by the detector is J_a, J_b, J_c, J_d, respectively. The scattering intensity obeys a Gaussian distribution as.

$$J(x) = \frac{J_0}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(x-x_l)^2}{2\sigma^2}\right] \tag{12}$$

where J_0 is calculated by (11).

The curve of (12) is shown in Fig. 6.

$J(x_l - 3\sigma) = J(x_l + 3\sigma) \simeq 0$, the width of laser beam can be replaced by 6σ approximately, that is $d = 6\sigma$. Therefore, on the left edge, there are

$$J(x_l) = \begin{cases} 0 & (x_l < x_1 - d/2,\ x_l > x_2 + d/2) \\ J_b & (x_1 + d/2 < x_l < x_2 - d/2) \\ J_0 - 6\int_{x_l-(d/2)}^{x_1} J_0 \dfrac{1}{\sqrt{2\pi}d}\exp\left[-\dfrac{18(t-x_l)^2}{d^2}\right]\mathrm{d}t & (x_1 \le x_l \le x_1 + d/2) \\ J_0 - 6\int_{x_2}^{x_l+(d/2)} J_0 \dfrac{1}{\sqrt{2\pi}d}\exp\left[-\dfrac{18(t-x_l)^2}{d^2}\right]\mathrm{d}t & (x_2 - d/2 \le x_l \le x_2) \\ 6\int_{x_1}^{x_l+(d/2)} J_0 \dfrac{1}{\sqrt{2\pi}d}\exp\left[-\dfrac{18(t-x_l)^2}{d^2}\right]\mathrm{d}t & (x_1 - d/2 < x_l < x_1) \\ 6\int_{x_l-(d/2)}^{x_2} J_0 \dfrac{1}{\sqrt{2\pi}d}\exp\left[-\dfrac{18(t-x_l)^2}{d^2}\right]\mathrm{d}t & (x_2 < x_l < x_2 + d/2) \end{cases} \tag{13}$$

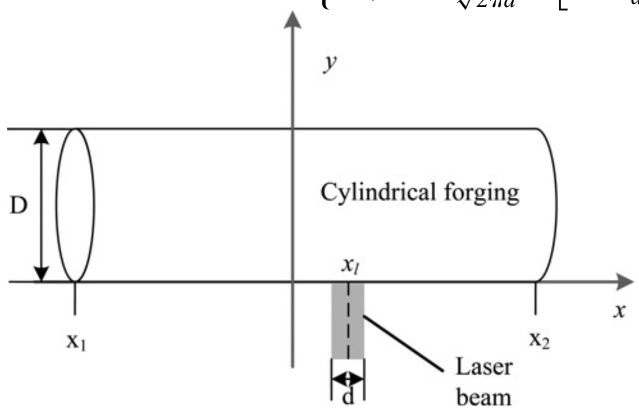

Fig. 5 *Schematic diagram of laser beam scanning the forging*

$$J_a = 0$$

$$J_b = 12\int_0^{d/2} J_0 \frac{1}{\sqrt{2\pi}d}\exp\left(-\frac{18(t-x_l)^2}{d^2}\right)\mathrm{d}t$$

$$J_c = J_b - 6\int_{x-(d/2)}^{x_1} J_0 \frac{1}{\sqrt{2\pi}d}\exp\left(-\frac{18(t-x_l)^2}{d^2}\right)\mathrm{d}t$$

$$J_d = 6\int_{x_1}^{x+(d/2)} J_0 \frac{1}{\sqrt{2\pi}d}\exp\left(-\frac{18(t-x_l)^2}{d^2}\right)\mathrm{d}t$$

Hence the scattering power in the process of scanning is (see equation (13) at bottom of next page)

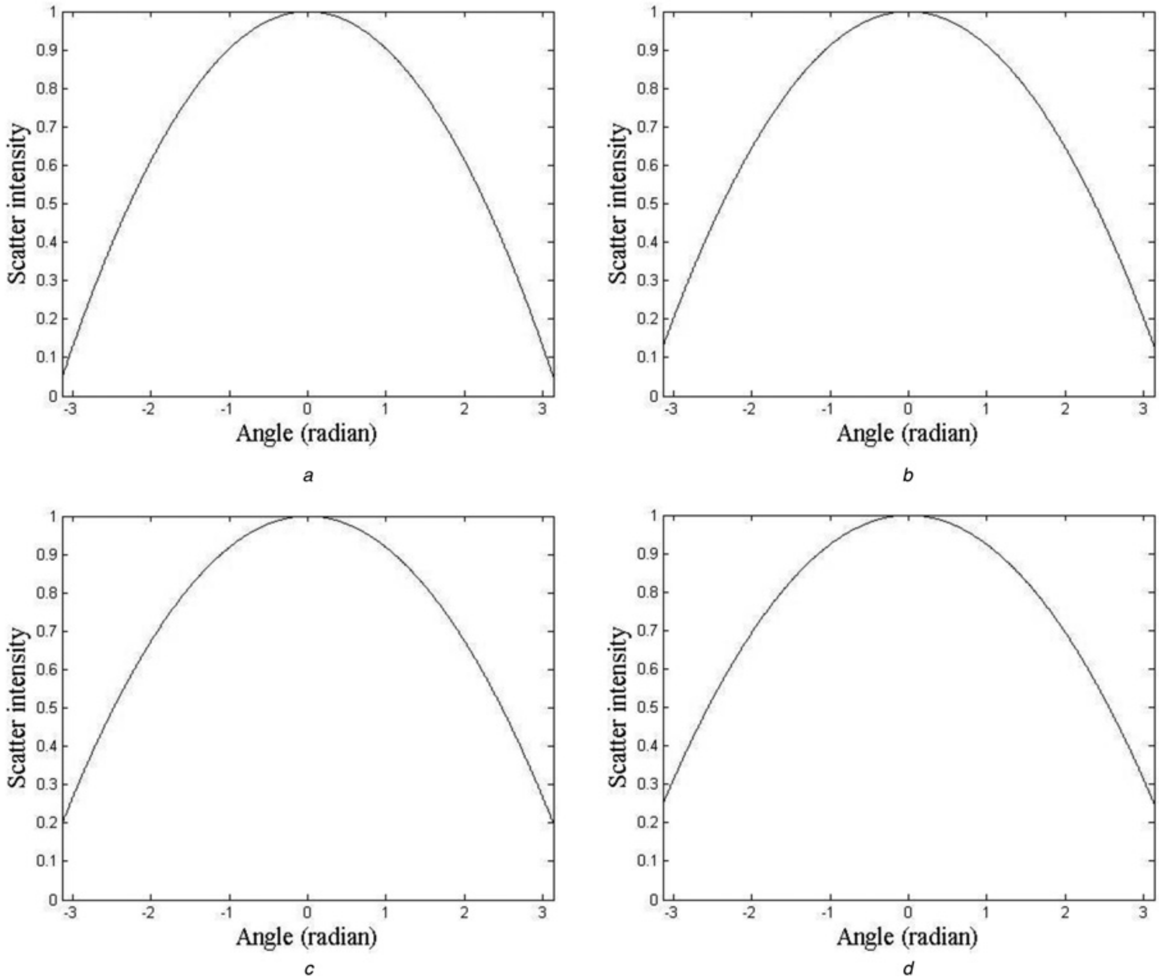

Fig. 7 *Scattering intensity curves*

a $k = 0.2$
b $k = 0.5$
c $k = 0.7$
d $k = 1.0$

We take the derivative with respect to $J(x_l)$, $J'(x_l)$ is:

$$J'(x_l) = \begin{cases} 0 & (x_l < x_1 - d/2, x_l > x_2 + d/2, \\ & x_1 + d/2 < x_l < x_2 - d/2) \\ \dfrac{108 J_0 (x_1 - x_l)^2}{\sqrt{2\pi} d^3} & (x_1 - d/2 \le x_l \le x_1 + d/2) \\ -\dfrac{108 J_0 (x_2 - x_l)^2}{\sqrt{2\pi} d^3} & (x_2 - d/2 \le x_l \le x_2 + d/2) \end{cases} \tag{14}$$

Substituting x_l into (14), when the $J'(x_l)$ reaches its maximum or minimum value, it means that the laser beam is on the edges of forgings in this moment.

4 Simulation and experiment

4.1 Simulation of the scattering model

According to (10) and (11), when $L_1 = 5$ m, $\theta = 1.5$ mrad, $\theta s = 0$, the diameter of the forging is 100 mm, the RMS slope $k = 0.2$, $k = 0.5$, $k = 0.7$, $k = 1$, the scattering power of cylindrical surface are calculated. The scatter intensity curves after normalised are shown as Fig. 6.

In Fig. 7, the abscissa is γ, which is the pitch angle of detector. As can be seen from Fig. 7, when $\gamma = 0$, the scattering intensity received by the detector is maximal. Therefore, when $\gamma = 0$, the measurement results will be more precise.

According to the conclusion above, when $\gamma = 0$, $x_1 = 1000$ mm, $x_2 = 1400$ mm, the scatter intensity curves of different d during the process of scanning are simulated, and the curves are shown in Fig. 7.

As shown in Fig. 8, the smaller the d is, the greater the slope of the curve is. As a consequence, the smaller the d is, the more accurate the result of the measurement is.

4.2 Experiment of size measurement

In the experiment, a standard cylinder forging is measured according to the process in Fig. 1. The standard cylinder forging is heated to 1200°C by electric furnace. As shown in Fig. 9. Then the cylinder forging is fixed on the workbench. As shown in Fig. 10. In order to reduce the influence of high temperature, a band-pass filter, central wavelength is 532 nm is fixed in front of the detector. The length of the standard forging is 396 mm at room temperature. When heated, the forging will expand. The hot forging was measured several times by calliper. The average length is 401.3 mm. Therefore, 401.3 mm was treated as the true length of the forging when heated. We make $\gamma = 0$ and $d = 2$ mm. When laser scanning the forging, the scattering intensity will change like Fig. 8. If $J'(x)$ reaches a maximum or a minimum, it means that the laser is on the edge of the forging. The difference of positions of two edges is the size of the forging. According to the method,

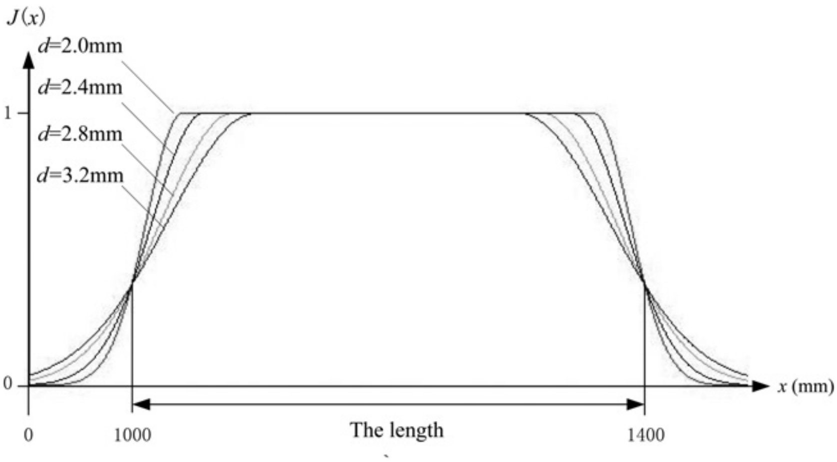

Fig. 8 *Scattering intensity curves of different d during the process of scanning*

Fig. 9 *Heating the forging*

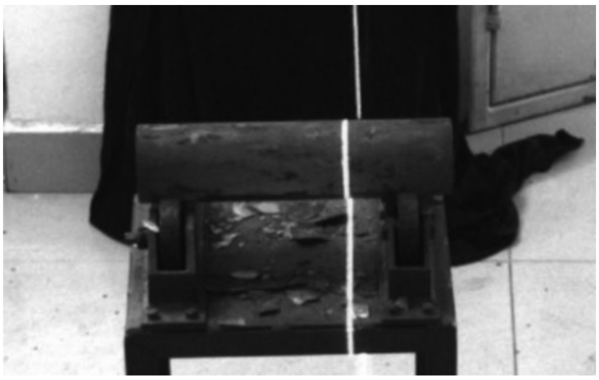

Fig. 10 *Experiment of measuring a forging*

Table 1 Measuring results

No.	The position of left edge, mm	The position of right edge, mm	The length, mm	Error, mm
1	2205.23	2605.59	400.36	0.94
2	2205.37	2605.36	399.99	1.31
3	2204.83	2605.11	400.28	1.02
4	2205.56	2606.43	400.87	0.43
5	2204.85	2605.22	400.37	0.93
6	2204.33	2604.89	400.56	0.74
7	2205.24	2605.02	399.78	1.52
8	2204.93	2604.46	399.53	1.77
9	2205.07	2604.55	399.48	1.82
10	2205.28	2606.49	401.21	0.09

the forging are measured at 10 times. The measuring results are shown in Table 1.

The accuracy is shown as.

$$\delta = \frac{\Delta}{R} \times 100\% \tag{15}$$

where δ is the accuracy, Δ is the maximum error of the measurement, R is the true value of measured object. According to Table 1, $\Delta = 1.82$ mm, $R = 401.3$ mm. The accuracy δ is $1.82/401.3 \times 100\% = 0.45\%$. It can meet the requirement of accuracy.

5 Conclusions

Combining the rough cylindrical surface scattering and servo control, an automatic size measurement method for hot forgings is proposed in this paper. Due to the edge detection based on scattering and pulse coder, the positional information not has to acquire by lots of point cloud data. Therefore, the method is able to achieve fast automatic measurement without complicated calibration. The system based on the method has been validated on regular forgings under laboratory conditions by the experiment. Measurement can be finished within 5 s. The experiment results show that the maximum measuring error is within 2 mm. In the forging field of hot state forging, error which is within 4 mm is enough accurate [19]. According to the principle of measurement, the measurement accuracy has little to do with the size of forgings. Therefore, it is proved that the method satisfies the requirement of large hot forgings measurement and the system is effective and efficient for size measurement of large hot forgings. Future work will aim at the measurement of irregular forgings.

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