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Comparisons of nozzle orifice processing methods using synchrotron X-ray micro-tomography*

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Abstract: Based on the high flux synchrotron X-ray of the Shanghai Synchrotron Radiation Facility (SSRF), high precision 3D digital models of diesel nozzle tips have been established by X-ray micro-tomography technology, which reveal the internal surfaces and structures of orifices. To analyze the machining precision and characteristics of orifice processing methods, an approach is presented based on the parameters of the internal structures of nozzle orifices, including the nozzle diameter, the orifice inner surface waviness, the eccentricity distance and the angle between orifices. Using this approach, two kinds of nozzle orifice processing methods, computerized numerical control drilling and electric discharge machining, have been studied and compared. The results show that this approach enables a simple, direct, and comprehensive contrastive analysis of nozzle orifice processing methods. When processing a single orifice, the electric discharge machining method has obvious advantages. However, when there are multiple orifices, the error levels of the two methods are similar in relation to the symmetry of distribution of the orifices.

Key words: Diesel nozzle, Internal structures, Orifice processing methods, Synchrotron X-ray micro-tomography
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1 Introduction

With diesel engine emission and fuel consumption regulations becoming more stringent globally, high efficiency and low-emission combustion in diesel engines are becoming key issues. In diesel engines, fuel is forced into nozzles and then injected into cylinders under pressure, usually of from 150 to 250 MPa. The sprays formed are of great significance for the fuel combustion process and the formation of emissions (Payri *et al.*, 2009; Som *et al.*, 2011). With increasing injection pressure, the spray becomes more sensitive to the internal geometries of the nozzle such as the inlet chamfer radius, the diameter, and the conicity level. Thus, more precise methods for the machining of diesel nozzles are required. Currently, there are four main processing methods for manufacturing diesel nozzles: hand drilling on a high-speed bench drill, computerized numerical control drilling (CNCD), electrical discharge machining (EDM) drilling, and laser processing drilling (Ren and Huang, 2008). As technology advances, hand drilling is being phased out. Laser processing drilling is still confined to laboratory studies and has not yet been applied to manufacture. The diesel nozzles on the market are produced mainly by the CNCD or EDM methods. Therefore, the comparison and analysis of the characteristics of these two processing methods are undoubtedly of great significance for the advancement of nozzle manufacturing technologies and for understanding diesel spray characteristics in cylinders.

However, as access to the internal structure for measurement is very limited in these micro nozzle orifices, nozzle orifice processing methods are

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usually compared by testing the macroscopic or microscopic characteristics of their sprays, which can indirectly reflect these processing characteristics to a certain extent (Gao *et al*., 2010). However, spray characteristics are affected by many factors including the injection pressure, the ambient pressure and the internal structures of the orifice. Therefore, a direct, quantitative analysis of nozzle orifice processing methods is not feasible merely through the spray characteristics.

A nozzle orifice's internal surfaces and structures can reflect its processing characteristics directly. Therefore, researchers all over the world have proposed quite a few methods to obtain the internal structures of diesel nozzles, including optical diagnostic methods (Wang and Hu, 2004; Diver *et al*., 2004), sectioning methods (Jung *et al*., 2008; Kostas *et al*., 2009), micro probe measuring methods (Kim *et al*., 1999; Kao and Shih, 2007; Peiner *et al*., 2009), a silicone molding method (Macián *et al*., 2003), a commercial X-ray method (Delphine *et al*., 2007), and a synchrotron X-ray micro-tomography method (Li *et al*., 2011). However, these methods are either destructive or inaccurate and inconvenient except for the synchrotron X-ray micro-tomography method. This method is nondestructive, has high precision (a spatial resolution of 9 μm can be achieved, which is much higher than that of commercial X-ray tomography), is rapid (around 15 min for measuring one nozzle), and is convenient for data processing (all data are in digital form and can be processed easily using computers). Thus, since its recent introduction, this method has become a unique and useful tool for the quantitative study of the internal structure of diesel nozzles.

In this paper, an approach for comparing and analyzing nozzle orifice processing methods is proposed using micro-tomography 3D digital models of diesel nozzle tips, developed using the high flux synchrotron X-ray of the Shanghai Synchrotron Radiation Facility (SSRF), China. The characteristics of the CNCD and EDM methods are compared and analyzed directly according to this approach.

2 Digital models of diesel nozzles

As the first third-generation synchrotron radiation facility in China, the SSRF has many advantages including a wide wavelength range, high intensity and high stability. It is widely used at the frontiers of medicine, physics, material and automotive research (Li *et al*., 2010). In this study, the internal structures of diesel nozzle tips were revealed on the X-ray Imaging and Biomedical Applications Beam Line (BL13W1) of the SSRF. The detailed features of this beam line have been described by Li *et al*. (2011). The experimental setup is sketched in Fig. 1a.

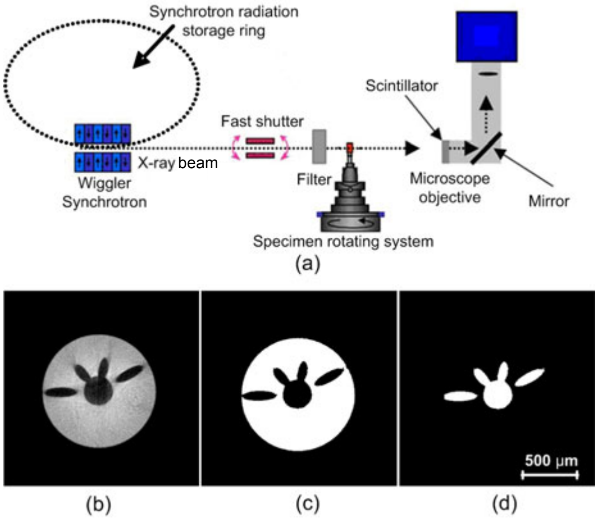
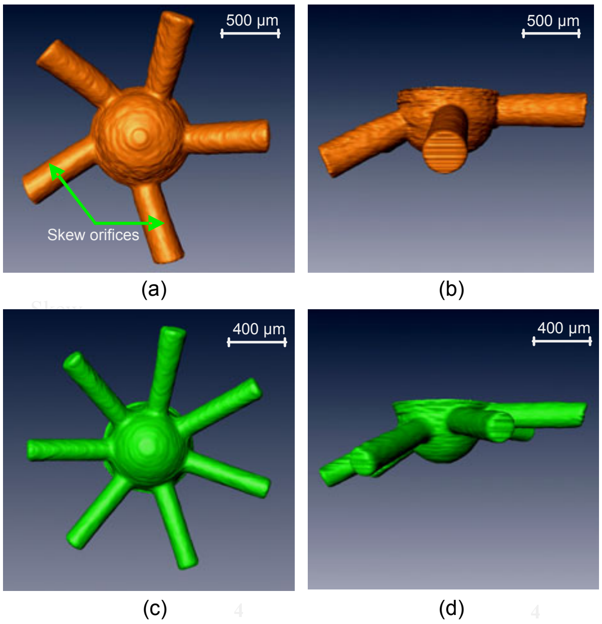


Fig. 1 (a) A sketch of the synchrotron X-ray micro-tomography setup at the beam line BL13W1 of the SSRF, (b) one original slice, (c) binary slice processed from (b), and (d) the reversal of (c)

The diesel nozzle is held on the specimen rotating platform. The synchrotron X-ray penetrates its tip and irradiates the scintillator to form absorption images in a charge-coupled device (CCD) camera. The pixel size of the CCD chip is 9 μm×9 μm and the chip is coupled to the scintillator by an optical fiber. The X-ray photon energy of this beam line was tuned to 50 keV and the exposure time was set to 160 ms. During the computed tomography (CT) scanning process, the specimen rotates 180° to obtain sufficient absorption images to generate slices. In accordance with the nozzle tip size and spatial resolution, a total of 900 absorption images were captured, and the slices were then reconstructed. Fig. 1b shows one original slice. By digital image processing the original slices were converted to binary slices and corresponding reversed slices to enhance the signal to noise ratio (Li *et al*., 2011) (Figs. 1c and 1d). By stacking these reversed slices, the 3D digital model of the diesel nozzle was constructed directly. Fig. 2 shows the digital models created by reversed slices. These are used conventionally to reveal the detailed internal surfaces and structures of the orifices and to measure their geometrical dimensions directly, such as the orifice diameter and the inlet chamfer radius.



(a) (b)

(c) (d)

Fig. 2 3D digital models of diesel nozzle orifices manufactured by the CNCD (a) and (b), and the EDM (c) and (d) methods

3 Internal structure parameters

3.1 Selection of characteristic parameters

Figs. 2a and 2b show the digital models of a tilt layout 5-orifice diesel nozzle processed by the CNCD method. Figs. 2d and 2e show the models of a tilt layout 7-orifice diesel nozzle processed by the EDM method. The differences between the two orifice processing methods can be seen clearly from these digital models. The surface finish of the EDM method is better than that of the CNCD method. From the outlet to the inlet of the orifice, the orifice diameters along the orifice axis are basically uniform in the EDM nozzle. Those of the CNCD nozzle are notably uneven, with the diameters adjacent to the outlet area being considerably larger than those near the inlet area.

To obtain a more scientific and quantitative comparison of processing method characteristics, a few internal structure characteristic parameters were defined or selected based on the 3D models. These parameters included: the surface waviness of each orifice, the nozzle inlet and outlet diameters, the eccentricity distance—the projected distance between the orifice axis and the symmetry axis, and the angle between the central axis of each pair of orifices (Fig. 3).

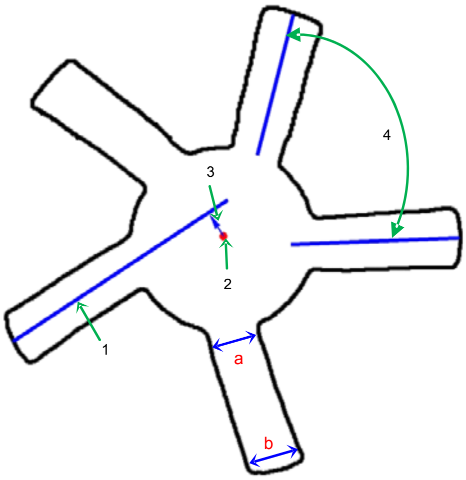


Fig. 3 Selection and definition of characteristic parameters of nozzle internal structures

1: orifice axis; 2: symmetry axis; 3: eccentricity distance; 4: angle between orifices; a: diameter of nozzle inlet; b: diameter of nozzle outlet

Currently, nozzle orifices are processed to form a tapering shape—the inner diameters are larger than the outer diameters, to gradually reduce the cross-sectional area of the orifice to meet the requirements of flow continuity and to decrease cavitation damage to the nozzle orifices. The inner and outer orifice diameters were chosen as the characteristic parameters for comparing processing methods, as they can reflect the *K* factors of the orifice directly.

To distribute diesel sprays more uniformly in the cylinder, nozzle orifices are designed symmetrically around the symmetry axis. Thus, the orifice axes are supposed to intersect with the symmetry axis if the orifices are distributed absolutely symmetrically. However, in reality the distribution can never be absolutely symmetrical due to machining errors. Therefore, the eccentricity distance was defined to represent this asymmetry. A smaller eccentricity distance indicates better symmetry, and is good for the enhancement of the flow coefficient. The angles between the orifices can also reflect the symmetry of the distribution of the orifices. The sprays will be distributed more symmetrically in the cylinder if these angles are more uniform, thereby enhancing air/fuel mixing and combustion in the cylinder.

At the micro level, the surface finish of the orifice is also significant for nozzles. As the spatial resolution of the method presented is 9 μm, when the wavelength of the surface roughness is smaller than 9 μm, it will be cut off like a kind of low-pass filter to generate surface waviness. Therefore, orifice surface waviness was also selected and measured for comparison of the orifice processing methods.

3.2 Measurement of characteristic parameters

The parameters of the internal structure characteristics of the CNCD 5-orifice nozzle and the EDM 7-orifice nozzle were measured according to the method described by Li *et al.* (2011). The measured inner and outer diameters and their standard deviations are shown in Table 1, and the top and bottom chamfer radii are listed in Table 2. As the two nozzles are tilt layout, the chamfer radii are different from each other.

Table 1 Inner and outer orifice diameters (μm) of the EDM and CNCD nozzles

Orifice	EDM nozzle		CNCD nozzle	
	Outer diameter	Inner diameter	Outer diameter	Inner diameter
1	185	189	323	296
2	168	183	327	290
3	176	178	318	300
4	187	187	322	307
5	183	185	326	300
6	182	191		
7	184	184		
Standard deviation	6.6	4.3	3.6	6.2

Table 2 Top and bottom chamfer radii (μm) of the EDM and CNCD nozzles

Orifice	EDM nozzle		CNCD nozzle	
	Top chamfer radii	Bottom chamfer radii	Top chamfer radii	Bottom chamfer radii
1	15	43	19	76
2	20	54	48	82
3	41	51	48	59
4	89	56	19	57
5	41	48	33	105
6	23	49		
7	21	46		

By the same approach, the eccentricity distances and angles between orifices were measured (Table 3).

Table 3 Eccentricity distances (μm) and angles (°) between orifices of the EDM and CNCD nozzles

Orifice	EDM nozzle		CNCD nozzle	
	Eccentricity distance	Eccentricity angle	Eccentricity distance	Eccentricity angle
1	5.1	48.9	45.5	72.4
2	11.8	52.4	45.4	67.1
3	8.0	49.6	96.0	71.2
4	19.6	50.7	137.4	75.1
5	25.0	57.4	102.9	74.3
6	15.8	52.1		
7	3.9	48.9		

4 Data analysis

4.1 Diameters

The nozzle orifice diameter plays an important role in the fuel atomization process. Table 1 shows the measured orifice diameters of the CNCD and EDM nozzles. The designed diameter of the CNCD nozzle is 320 μm and that of the EDM nozzle is 180 μm. It is difficult to process tiny orifices using the CNCD method due to its accuracy limitations and the hardness requirements of its drill. Using the EDM method, only a discharge rod is needed and this rod can be processed thinly as there is little hardness requirement.

The standard deviations of the two methods are similar, and the diameters are close to the design diameters (Table 1). However, the design diameter of the CNCD method is almost twice as large as that of the EDM method, indicating that the processing accuracy of the EDM method is higher than that of the CNCD method.

Many studies have confirmed that the *K* factor of a nozzle orifice has important effects on the spray characteristics (Payri *et al.*, 2008). This parameter, which is directly related to the orifice diameter, was used in this study to evaluate the orifice processing methods. The following expression defines the *K* factors of nozzle orifices:

$$K = \frac{D_{\text{in}} - D_{\text{out}}}{10},$$

where D_{in} and D_{out} represent the inner and outer diameters of orifice (μm), respectively. So when D_{in} is greater than D_{out}, the K factors will be positive, which is good for the enhancement of the flow coefficient and the life of the nozzle. The K factors of the two methods are compared in Fig. 4. Using the CNCD method it is very difficult to process the orifices in positive K as the drill is in the form of a negative tapering shape. The K factors of the CNCD nozzle are all negative (Fig. 4). However, using the EDM method the orifices can be processed in a spiral manner through a thin discharge rod. The outer diameter can thereby be processed to be smaller than the inner diameter, thus meeting the processing requirements of modern nozzles according to the previous analysis.

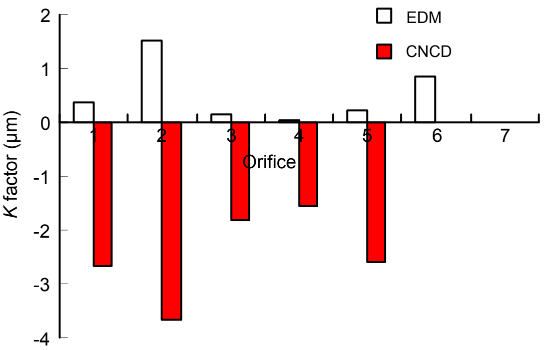


Fig. 4 *K* **factors of the orifices processed by the EDM and CNCD methods**

4.2 Surface waviness

While producing the nozzles, the orifices are all processed by hydro-grinding to guarantee the flow coefficient. So the surface roughness of the orifices is supposed to be similar. However, the orifice surface waviness of the two nozzles may be different due to different drilling methods. The surface waviness of the two nozzles was obtained and compared by digital image processing, and the results are shown in Figs. 5a and 5b.

The curvatures of the EDM nozzle's inner surface are smoother than those of the CNCD nozzle. From these curves, W_a, W_p and W_v of the surface waviness were calculated (Table 4). The mean value of W_a of the EDM nozzle was 1.21 μm while that of the CNCD nozzle was 1.79 μm, and the mean values of W_p and W_v of the CNCD nozzle were larger than those of the EDM nozzle. Thus, the inner surface finish of the EDM method is better than that of the CNCD method.

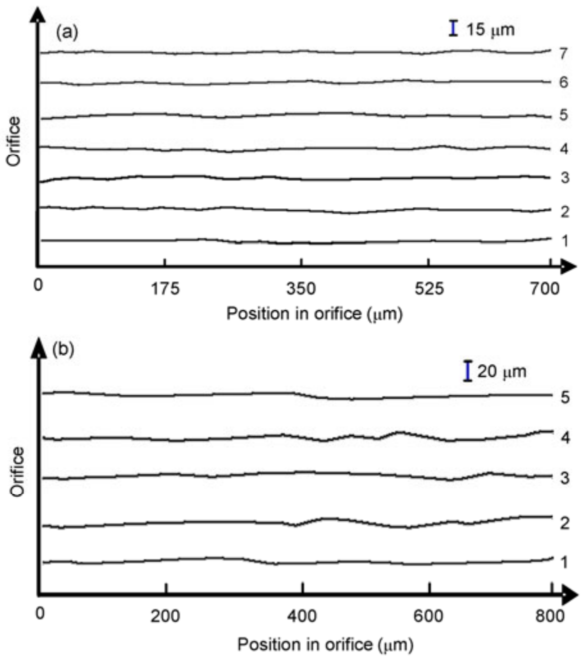


Fig. 5 Inner surface waviness of the (a) EDM and (b) CNCD nozzles

Table 4 W_a **(μm),** W_p **(μm) and** W_v **(μm) of the surface waviness of the EDM and CNCD nozzles**

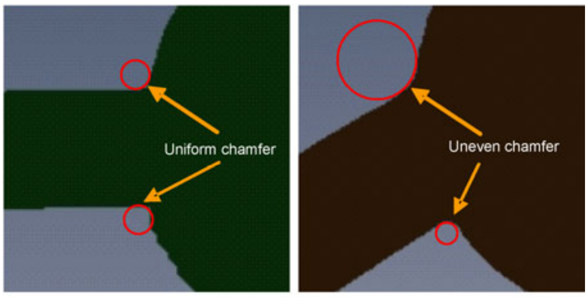
Orifice	EDM nozzle			CNCD nozzle		
	W_a	W_p	W_v	W_a	W_p	W_v
1	1.07	2.45	3.49	1.55	2.77	4.46
2	1.57	5.38	3.73	2.21	5.04	6.18
3	1.14	5.41	2.29	1.78	4.86	3.85
4	1.23	4.04	3.40	1.75	3.15	6.71
5	1.39	3.63	3.08	1.66	4.63	3.74
6	1.25	3.39	3.06			
7	0.80	2.29	2.66			
Mean value	1.21	3.80	3.10	1.79	4.09	4.99

4.3 Eccentricity distance

The orifice eccentricity distance can reflect the uniformity of the orifice inner chamfers, which are formed where the orifice intersects the nozzle sac (Fig. 6)

Fig. 6a shows one orifice processed by the EDM method. The eccentricity distance of this orifice is 19.6 μm. Fig. 6b shows an orifice drilled by the

CNCD method. Its eccentricity distance is 137.4 μm. The chamfer formed in Fig. 6a is basically uniform, however, the chamfer formed in Fig. 6b is uneven, with the two chamfer radii differing widely. Based on simulation studies, the uneven chamfer will cause a decline in the flow coefficient, and on the smaller radius side, the cavitation will increase and cause earlier damage to the nozzle. Fig. 7 shows the eccentricity distance of the two nozzles processed by different methods. The orifice eccentricity distance of the CNCD nozzle is about ten times larger than that of the EDM nozzle. When processing by the CNCD method, the drill may bend due to its small diameter and the high hardness of the nozzle tips. Then the boring direction may deviate from its original direction and cause a large eccentricity distance. However, with the EDM method, the discharge rod will keep its direction when processing. It sustains only small forces when discharging sparks to melt the nozzle tip, which ensures the centrality of the orifices.



(a)   (b)

Fig. 6 Chamfers formed by orifices of different eccentricity distances. The eccentricity distance is 19.6 μm in (a) and 137.4 μm in (b)

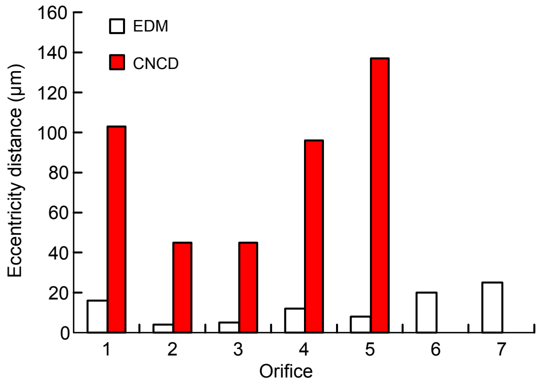


Fig. 7 Eccentricity distances of orifices processed by the EDM and CNCD methods

4.4 Angle between orifices

No matter whether a nozzle is tilt layout or centrality layout, the orifices are required to distribute symmetrically. If the nozzle is centrality layout, the symmetrical axis will overlap with the nozzle axis; otherwise not. For 5-orifice nozzles, in ideal conditions the angle between orifices should be 72°, while for 7-orifice nozzles the ideal angle should be 51.4 °. The angles between the orifices of the two nozzles in this study are listed in Table 3. The maximum angle of the CNCD nozzle was 75.1°, the minimum was 67.1°, and the maximum deviation was 5°. The maximum and minimum of the EDM nozzle were 57.4° and 48.9°, respectively, and the maximum deviation was 6°. The angle deviations of these orifices are shown in Fig. 8. The deviations are both relatively large, and the error level is similar for each of the two processing methods.

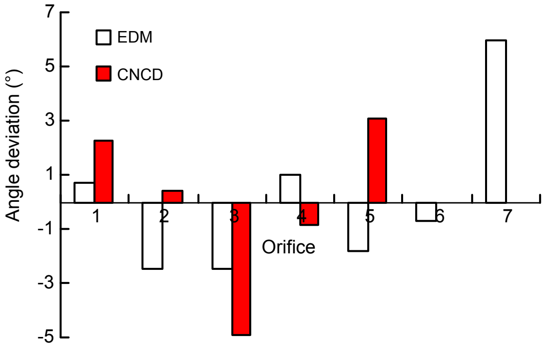


Fig. 8 Deviations in the angle between orifices processed by the EDM and CNCD methods

Although the two nozzles were processed by different orifice processing methods, the mechanisms which were holding and rotating the nozzle while processing the orifices were similar. So the centrality performance of the two methods was quite similar. Although the EDM method has significant advantages in processing orifices, due to the similar rotation mechanism, there is no obvious difference between the orifice symmetries of the two processing methods.

5 Conclusions

Based on synchrotron X-ray micro-tomography, high precision and high resolution 3D digital models of nozzle tips were established. According to the models, the internal structures of nozzles can be revealed, and their characteristics parameters can be defined and measured. This enables the direct comparison of the characteristics of different orifice processing methods. The inner and outer diameters, the surface waviness, the eccentricity distance and the angle between orifices can be used to analyze the orifice processing characteristics of different methods. The following conclusions can be drawn.

1. The approach presented to analyze the characteristics of different orifice processing methods has been confirmed to be a rapid, simple, direct and comprehensive analytical tool.

2. According to the orifice structures and surface finish, the EDM method is better than the CNCD method in terms of accuracy and controllability when processing a single orifice; however, in terms of the angles between orifices, the symmetry accuracies of the two methods are passable, and their error levels basically the same.

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