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New Measures for Prolonging the Nozzle Service Life

Yuan Changjun[1, *], Liu Zongchang[2]

[1]Heze Guangxin Marine Parts & Fuel Injection Equipment Co., Ltd, Heze, People's Republic of China

[2]Material and Metallurgy School, Inner Mongolia University of Science and Technology, Baotou, People's Republic of China

Email address:
ycjycy198123@126.com (Yuan Changjun)

[*]Corresponding author

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Abstract: Microstructures of 27SiMnMoVA steel intended for nozzle in raw, as-brazed and as-normalized states were surveyed by using OLS4000 laser scanning confocal microscope, Axiovert-25CA optical microscope and QUENTA-400 scanning electron microscopy. It is found that the microstructures of raw 27SiMnMoVA steel are ferrite and pearlite; the microstructures of the as-brazed 27SiMnMoVA steel are ferrite, martensite, bainite and troostite; the microstructures of as-normalized 27SiMnMoVA steel are sorbite and bainite; and that the as-normalized microstructures are appreciably finer than the as-brazed microstructures. Adjusting the carburizing and hardening processes, a cryptocrystalline martensite provided with better wear-resistance is obtained in the case of 27SiMnMoVA steel specimen, and the effective hardened depth is increased from 0.48mm to 0.75mm. Retained austenite content and wear-resistance of the 27SiMnMoVA steel specimens in different heat treatment conditions were measured by means of D8 Advance X-ray diffractometer and MM200 Pin-on-Disk wear testing machine. The results show that the retained austenite contents in the specimens are six to eight percent, and the abrasion marks are as about 3mm. The volume and superficial area of the cooling chamber were increased by 13% and 23% respectively by the way of improving it's structure, which made the cooling performance of the needle nozzle enhanced significantly. The purpose of increasing the flow coefficient of the nozzle spray holes, improving the spray quality and performance of the nozzle and prolonging the nozzle assembly service life were achieved by adopting liquid extrusion grinding process and carried out the liquid extrusion grinding in spray holes of the nozzle by using KYM-2 liquid extrusion grinder.

Keywords: 27SiMnMoVA Steel, Nozzle, Retained Austenite, Effective Hardness Case, Wear Resistance, Liquid Extrusion Grinding, Flow Coefficient, Service Life

1. Introduction

The injector nozzle is one of the key precision parts in the diesel engine, it is an important research subject at home and abroad to improve the quality and durability of injector nozzle. The diesel injector is a key component of the diesel fuel injection system, and the injector nozzle is the core parts of the diesel injector, the high-pressure oil in the diesel engine is injected into the cylinder through the injector nozzle to obtain power after combustion, the injector nozzle quality will directly influence on the overall performance of diesel engine [1]. The injector nozzle served under extremely poor working conditions, such as high temperature, high pressure, impact and corrosion, thus, the injector nozzle should with high wear resistance, high hardness, high dimensional stability, enough toughness and better tempering stability and high contact fatigue strength, which make higher requirement for the material selection and heat treatment of the injector nozzle [2, 3].

The low service life of cooling injector nozzle is a technical tackling project of our company. This paper mainly discusses on metallographic structure, microhardness, retained austenite content, cooling chamber structure and spray holes liquid extrusion grinding.

2. Experimental Materials and Procedure

In this paper, we used the 27SiMnMoVA round bar which producted by Baosteel Special Metals Long Product Co., Ltd and the semi- manufactured injector nozzle made of

27SiMnMoVA round bar, cut the specimens for the retained austenite contents measured and wear test with the sizes of 20×20×4mm and 10×10×35mm respectively, normalized the nozzle after brazing, the specimens were treated by carburizing, quenching, cooling and tempering heat treatment processes. The microstructures of the specimens were observed by using OLS4000 laser scanning confocal microscope, Aviovert-25CA optical microscope and QUANTA-400 environmental scanning electron microscope, the retained austenite content and wear-resistance of the 27SiMnMoVA steel specimens in different heat treatment conditions were measured by means of D8 Advance X-ray diffractometer and MM200 Pin-on-Disk wear testing machine. The liquid extrusion grinding in spray hole of the nozzle is conducted in KYM-2 liquid extrusion grinder. The chemical composition of the tested 27SiMnMoVA steel is shown in Table 1.

Table 1. *Chemical composition of the tested 27SiMnMoVA steel (mass fraction,%).*

C	Si	Mn	Mo	V	P	S
0.27	1.21	1.42	0.45	0.27	0.010	0.017

3. Results and Discussion

3.1. Metallographic Observation

The injector nozzle is compared to the heart cardiac of the diesel engine, it is composed of nozzle and needle valve [4]. When working, the needle valve makes high frequency reciprocating motion in the nozzle, the sealing face is the main work site of the nozzle, the nozzle inner hole and the needle valve surface pay the functional guiding role. The microstructure and performance of the nozzle inner hole is directly determined it's service life and quality [5]. The cooling chamber of the cooling nozzle is formed of cooling water jacket and nozzle body matrix through brazing, the sketch of the as-brazed nozzle is shown in Figure 1. Due to brazing unique advantages of connecting thin-walled parts and dissimilar materials structure, it is gradually become an irreplaceable important connecting technology in precision machinery manufacturing. In order to ensure the brazing quality of the nozzle, T3 copper filler with better fluidity was adopted. Because of high brazing temperature and long holding time, the nozzle local microstructure must be transformed [6]. The microstructures of 27SiMnMoVA steel in original and as-brazed conditions are shown in Figure 2.

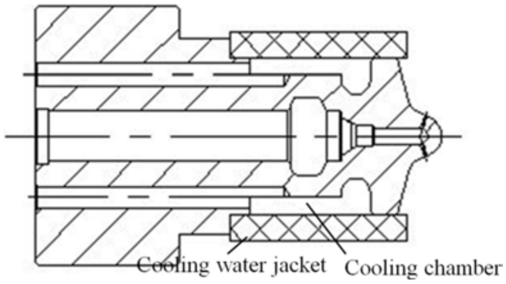

Figure 1. *As-brazed sketch of the 27SiMnMoVA steel needle nozzle.*

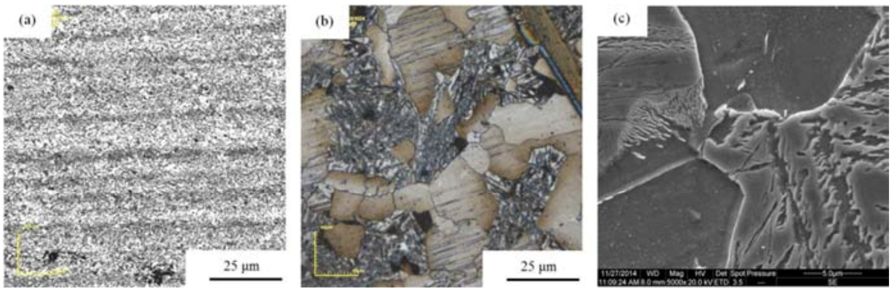

Figure 2. *Microstructures of 27SiMnMoVA steel in (a)original and (b, c) as-brazed conditions.*

By observing Figure 2 closely, it is founded that the microstructures of the raw 27SiMnMoVA steel are ferrite and pearlite, and the banded structures shown obviously which size class numbers are 4 according to the standard metallographic photos [7]. The microstructures of the as-brazed 27SiMnMoVA steel are ferrite, martensite, bainite and troostite, and the grain grows obviously. We adopted the annealing process showed in Figure 3 to eliminate the banded structure of the raw 27SiMnMoVA steel and the normalizing process showed in Figure 4 to refine grain of the as-brazed nozzle. Due to the poor sealing of the heating furnace, normalizing must be caused oxidation to a certain degree, severely oxidation can make the nozzle scrap, we carried out the comparative normalizing experiment under protect and non-protect heating conditions. The as-annealed and as-normalized microstructures are shown in Figure 5.

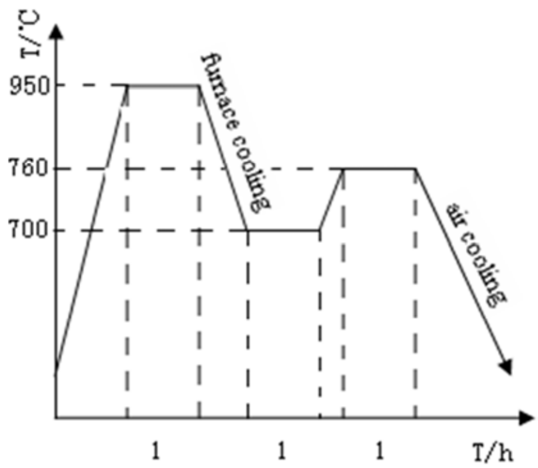

Figure 3. *Annealing process.*

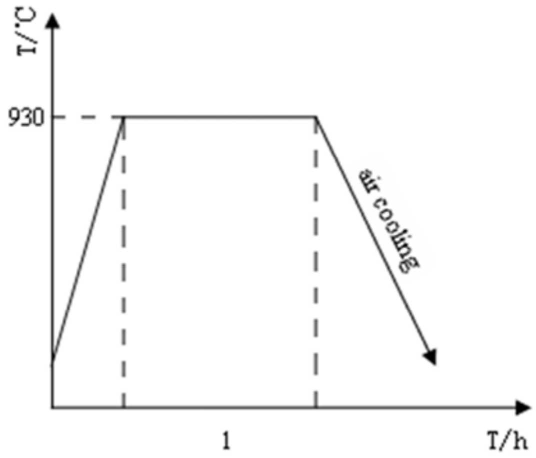

Figure 4. *Normalizing process.*

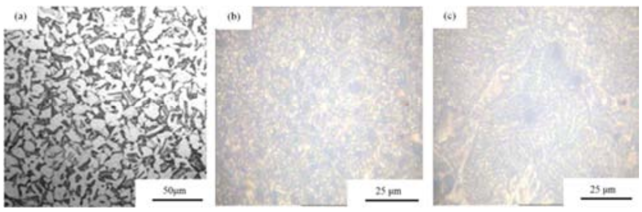

Figure 5. *Microstructures of (a) as-annealed and (b, c) as-normalized 27SiMnMoV steel.*

Essentially, the banded structure is caused by the segregation of alloy elements which along the forging rolling direction. The banded structure makes the mechanical properties of metallic materials shown directivity, especially reduced the transverse toughness significantly, and also makes the cutting performance become worse. The banded structure makes the structure stress and the tendency of deformation and cracking increase. The as-annealed microstructure of the raw 27SiMnMoVA steel is shown in Figure 5 (a), it's banded structure was eliminated. The raw 27SiMnMoVA steel was fully annealed at 950°C, insulation for 1 hour after furnace-cooling to 700°C to make the eutectoid decomposition occurred, then heated to 760°C within the temperature ranges of the dual-phase regions, the supersaturated carbon atoms diffusioned to austenite from ferrite, the alloy elements such as Silicon, Manganese, Molybdenum and Vanadium in the austenite diffusioned to ferrite, these two diffusion processes made the alloy elements distribution became homogenization, ultimately, the carbon and alloy elements redistributed [8]. Molybdenum and Vanadium have stronger affinity with carbon, which makes partial carbon atoms diffusion from austenite, and then carbon atoms distribution become homogenization. Air cooling makes carbon and alloy elements maintain redistributed state, thus the banded structure was eliminated.

The as-normalized microstructures under non-protect and protect heating conditions are shown in Figure 5 (b) and Figure 5 (c) respectively. It is found that the as-normalized microstructures are appreciably finer than the as-brazed microstructures by Comparing Figure 2 (b) with Figure 5 (b, c), and the grains in Figure 5 (c) are larger than that in Figure 5(b). The air cooling rate of the normalizing treatment under protect heating condition is slower than that under non-protect heating condition, the grains precipitated from austenite are relatively few because of slow cooling rate, and the refining effect of grain is relatively poor.

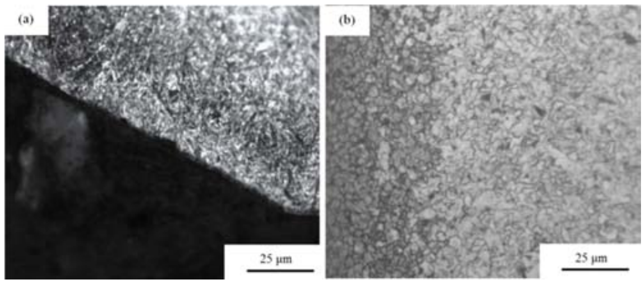

Figure 6. *Microstructures of the nozzle carburized layer by (a) original process and (b) improved process.*

The martensite morphologies of the case play a decisive role in the wear resistance and service life of the injector nozzle. The high hardness and brittleness characteristics of the acicular martensite lead to less toughness, the sharp-angled effect of the cupola where carbon potential is higher in carburizing treatment which resulted in formation of netlike carbides, and it broke the connection of the body and fatigue strength of the cupola was lower. Under the function of the high and alternating oil pressure micro-crack was easily formed in cupola of the injector nozzle and expanded in use which caused fracture. The ideal microstructures of the carburize layer are cryptocrystalline martensite and disperse carbide which further raise the toughness under the prerequisite of obtaining high surface hardness.

The microstructures of the carburized layer shown in Figure 6 (a) are acicular martensite which obtained under the original heat treatment process of austenitizing at 890°C for 1.5 hours and then quenching in 80°C hot-oil. It indicated that the matensite growth bigger and became more brittleness, the tendency of cracking increased, wear resistance decreased and quenching microcracks easily to cause when austenite of homogeneous chemical composition. Research shown that the longer acicular martensite the more microcracks [9].

The microstructures of the carburized layer shown in Figure 6 (b) are cryptocrystalline martensite which obtained under the improved heat treatment process of austenitizing at 860°C for 1.5 hours and then quenching in 80°C hot-oil. It indicated that more amount of undissolved carbide and higher hardness were gained when austenite of non homogeneous chemical composition. The cryptocrystalline martensite formed because of austenite of non homogeneous chemical composition. The dislocation lines bent when the moving dislocations encountered fine carbides, the dislocation loops formed around the fine carbides when the applied stress continue to increase, the rest dislocation lines continue to move. The formed dislocation loops also have some hindrance effect on the next dislocation line, the plastic deformation resistance improved further more due to the hindrance of the dislocation lines moving, at last the steel strengthening [10]. Therefore, the cryptocrystalline martensite has better performance than that of the acicular martensite.

3.2. Microhardness Gradient

In order to prevent peeling off and pitting corrosion from the nozzle surface during the course of carburization and quenching, the carbon concentration must be kept a smooth transition. The wear resistance is determined by the surface hardness and the microhardness gradient of the nozzle, the carbon concentration of the nozzle is controlled by adjusting carburizing process parameters, then affects the microhardness gradient of the nozzle. The original and improved carburizing processes are shown in Figure 7.

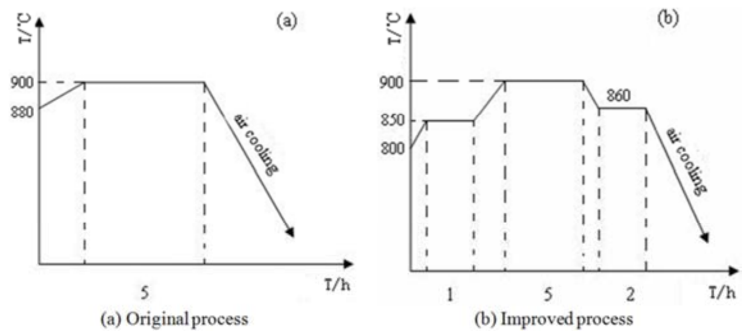

Figure 7. *Carburizing processes for the 27SiMnMoVA steel.*

Based on the data [11], the carburizing tank hot charging temperature is no less than 800°C, in order to ensure the carburized case uniformity and coincidently, the temperature uniformity in the carburizing tank must be ensured through burning thoroughly at 800~850°C after the carburizing tank furnace charging, in order to decrease the surface carbon concentration and increase the carburized case depth, the workpiece cooling in the carburizing tank to 840~860°C and thermal insulation for a period of time after carburizing, then air cooling to room temperature. The nozzle original carburizing process is furnace charging at 880°C and carburizing at 900°C, without preheating period and diffusion period, there is no guarantee that the temperature of the workpiece in different positions in the carburizing tank uniformity and coincidently during the carburizing beginning period. In order to ensure the nozzle carburized case uniformity and coincidently in the same batch as far as possible, the improved carburizing process was formulated, as shown in Figure 7 (b). The carburized and hardened effective case under the original and the improved processes are shown in Figure 8.

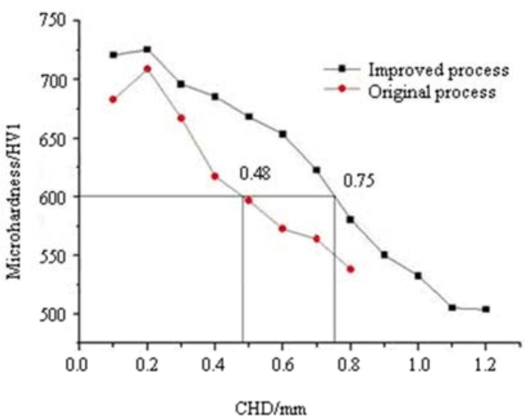

Figure 8. *Effective hardened case of the seat of 27SiMnMoVA steel nozzle carburized by original and improved processes then hardened.*

The sealing face is the main work site of the nozzle, therefore, we carried out the microhardness test at the sealing face and drawn the curves shown in Figure 8 by means of computer with the data tested. According to the GB/T9450-2005 standard [12], the standard is still in effect when the steel microhardness at the distance of 3 times case-hardened depth is higher than 450HV1, the premise is that select a certain specific microhardness value higher than 550HV1 as the boundary microhardness. The matrix microhardness of the carburized and hardened 27SiMnMoVA steel nozzle is about 500HV1, so select 600HV1 as the boundary microhardness of the carburizing and hardening effective case depth, the carburizing and hardening effective case depth of the nozzle seat under the original and improved processes are 0.49mm and 0.75mm respectively. It is found that the carburizing and hardening effective case depth obtained by the improved process is thicker than that obtained by the original process, and the microhardness gradient under the improved process became much more smoothly, which are beneficial to prolong the nozzle service life.

Observed Figure 8, we found that the carburized case microhardness decreased gradually from outside to inside, however, the microhardness value at 0.1mm to the surface is slightly lower than that at 0.2mm to the surface, this is the phenomenon of microhardness phubbing mentioned in document appeared [13]. The main reason is that the higher retained austenite, the lower hardness.

3.3. Retained Austenite Content and Wear Resistance

Different amounts of retained austenite exist in the microstructure of the carburized steel parts after carburizing and quenching. On the one hand, the retained austenite has the harmful effects of reducing hardness, decreasing dimensional stability and producing grinding cracks easily; on the other hand, the retained austenite is conducive to improving the strength and toughness of steel, retarding efficiently the crack growth and making the crack tip blunt or bifurcate. Under high stress and low cycle fatigue condition, with a moderate increase of the retained austenite, the fatigue life is improved

[14]. Wear resistance is an important technical index of the nozzle, different retained austenite contents are suitable for different environments, under relatively low stress state, the lower retained austenite content, the better wear resistance, while under relatively high stress state, the higher retained austenite content, the better wear resistance [15]. Thus, only a moderate amount of retained austenite can have a beneficial effect on the properties of steel. Given this, retained austenite content and wear resistance of the 27SiMnMoVA steel specimens in different heat treatment conditions were tested.

The retained austenite content of the 27SiMnMoVA steel specimens was measured by means of D8 Advance X-ray diffractometer, the X-ray diffraction conditions are Cu Ka radiation, graphite monochromator filtering, tube voltage (80KV), tube current (40mA), scan range (20°~90°), scan rate (°/min).

The wear resistance of the 27SiMnMoVA steel specimens was tested by means of MM200 Pin-on-Disk wear testing machine, the width of grinding was measured by means of JC10 read-microscopy, grinding wheel speed (200r/min), grinding wheel specifications (Φ40×10mm), grinding wheel material (W18Cr4V), the friction duty is dry grinding, applied load (3kg), friction time (30min). We carried out each wear test for each specimen at different positions three times and take the mean to eradicate any discrepancies.

The 27SiMnMoVA steel specimens were austenized at 890°C for 1.5 hours and then quenched in 80°C hot-oil, finally subzero treated under the subzero treatment process parameters shown in Table 2 after the No.1-5 and the No.6-7 specimens air cooling for 3 hours and 8 hours respectively. The retained austenite contents and the abrasion marks widths are shown in Figure 9.

Table 2. *Subzero treatment process parameters for the 27 SiMnMoVA steel nozzle.*

No. / Time/h / Temperature/°C	1	2	3	4	5	6	7
-60	1.5	2				1.5	
-70			1.5	2			1.5
-80					1.5		

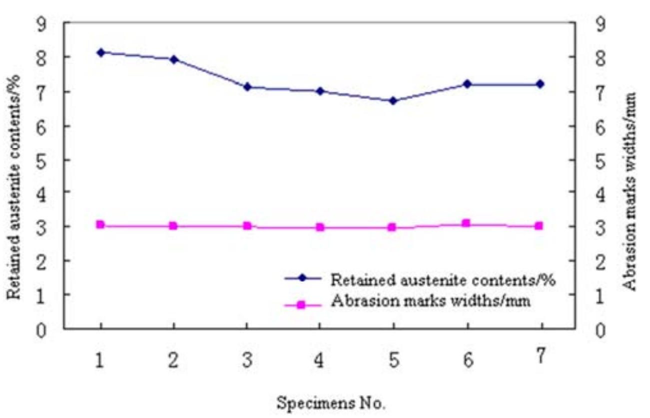

Figure 9. *Abrasion marks widths corresponding to retained austenite amounts for the 27SiMnMoVA steel samples.*

It is found from the retained austenite content curve shown in the Figure 9 that the retained austenite contents in the specimens are between 6% and 8%. The No.1 specimen with the highest retained austenite content, while the No.5 specimen with the lowest retained austenite content, combine the subzero treatment parameters in table 2, it can be seen that the lower subzero treatment temperature, the less retained austenite content; the retained austenite content in the No.2 specimen is less than that in the No.1 specimen, the retained austenite content in the No.4 specimen is less than that in the No.3 specimen, combine the subzero treatment parameters in table 2, it can be seen that prolong the subzero treatment time can make the retained austenite transformed more thoroughly.

It is found from the abrasion marks widths curve shown in the Figure 9 that the abrasion marks widths curve is in planes roughly parallel to the horizontal axis and the abrasion marks are as wide as about 3mm. It is shown that the wear resistance is similarly when the retained austenite contents in the specimens are 6% to 8%.

3.4. Improvement of Cooling Chamber Structure

The injector nozzle is the key part of the fuel injector, which mounted the top of cylinder according to design angle, the needle valve makes high frequency reciprocating motion in the nozzle under the action of high pressure oil, then fuel is injected into the cylinder by the constant impact of the needle valve. The better temper resistance of the nozzle was requested because of higher temperature in the cylinder. The cooling type nozzle usually burning heavy oil, the heavy oil need heating to higher than 100°C for using, which raises the temperature of the nozzle head. When the temperature exceeds 176°C, the fuel will decompose and form carbon deposits, which makes the nozzle spray holes jam and accelerates wear failure [16, 17]. Therefore, the structure of the cooling chamber should be designed reasonably to improve the cooling effect as far as possible, so as to prolong the nozzle service life. The original and improved cooling chamber sketches are shown in Figure 10. The original and improved volume and superficial area of the cooling chamber are shown in Table 3.

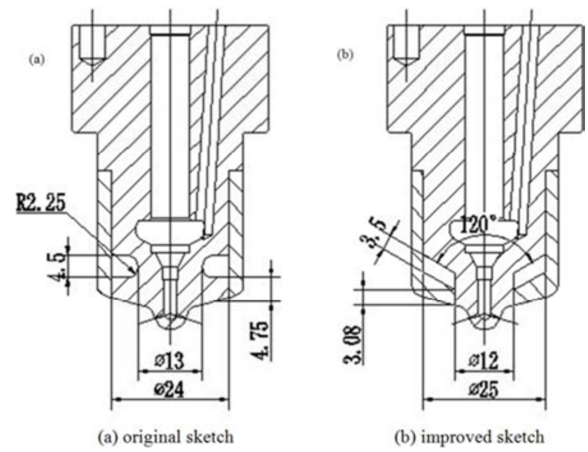

Figure 10. *Cooling chamber sketches of the nozzle.*

Table 3. *Volume and superficial area of the cooling chamber.*

Volume (mm^3)		Superficial area (mm^3)		Volume increase rate (%)	Superficial area increase rate (%)
original	improved	original	improved		
1.34×10^3	1.51×10^3	1.09×10^3	1.34×10^3	13	23

Figure 10 shows that the improved inside diameter of the cooling chamber is 1mm smaller than that of the original, meanwhile the improved outside diameter of the cooling chamber is 1mm bigger than that of the original, and the improved distance between the cooling chamber and the nozzle head is about 1.5mm shorter than that of the original. From table 3, compared with the original, the volume increase rate and superficial area increase rate were increased by 13% and 23% respectively after improvement. As a result, modification for the improvement of the cooling effect is proposed, which effectively decreases the working temperature of the nozzle head and greatly prolong the service life of the nozzle.

3.5. Liquid Extrusion Grinding in Spray Holes

The nozzle spray holes were machined following three steps of point drilling, drilling and reaming by five-axis CNC-drilling machine X6, the tolerance is within 0.005mm, the processing quality of the spray hole machined by five-axis CNC-drilling machine X6 is better than that machined by pneumatic bench drilling machine or high frequency and speed bench drilling machine, the flow coefficient can reach about 0.6. The size of the flow value and flow coefficient of the injector nozzle are directly influence the key performance indicators of the diesel engine, such as the power, specific fuel consumption, emission, and so on. Applying liquid extrusion grinding technique can decrease the surface roughness, reduce the fuel injection resistance and increase the flow coefficient of the nozzle spray holes. At present, the high-level engine requires the flow coefficient of the injector nozzle to reach above 0.8 [18, 19], in order to improve the flow coefficient further more, the liquid extrusion grinding in spray hole of the nozzle is conducted in KYM-2 liquid extrusion grinder, and detected the flow value of the nozzle by using an automatic detecting machine LDM-5 for high-press liquid flow. The images of the nozzle spray holes before and after extrusion grinding are shown in Figure 11, the flow values of the nozzle before and after extrusion grinding are shown in Table 4.

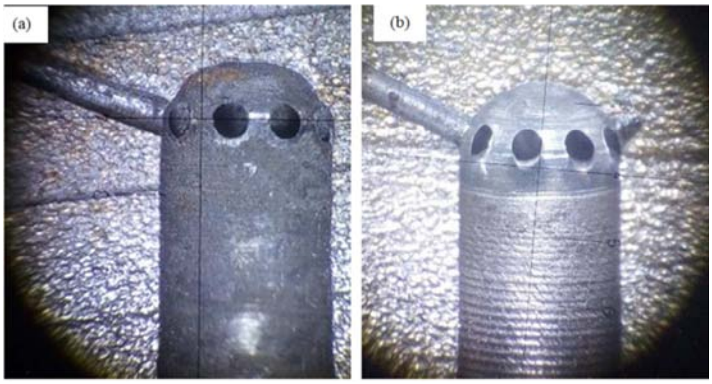

Figure 11. *Images of the nozzle spray holes before (a) and after (b) extrusion grinding.*

Figure 11 shows that burr and flanging exist in the inside edge of the spray holes, and the spray holes with rough surface before extrusion grinding. The burr and flanging which exist in the inside edge of the spray holes were removed effectively, an arc transition formed at the inside edge of the spray holes and the spray holes surface became smoother after extrusion grinding, which can reduce the fuel injection resistance significantly, improve the spray quality, increase flow value and flow coefficient, tackle defects of combustion lag and incomplete combustion. Finally, a virtuous cycle of diesel engine combustion system formed.

Table 4. *Flow values of the nozzle before and after extrusion grinding.*

No.	Flow values (L/Min)		No.	Flow values (L/Min)		No.	Flow values (L/Min)	
	before	after		before	after		before	after
1	6.969	9.253	11	6.731	9.299	21	6.592	9.385
2	7.122	9.536	12	6.822	9.241	22	6.735	9.343
3	6.863	9.324	13	7.052	9.382	23	6.895	9.451
4	7.039	9.276	14	7.106	9.418	24	7.028	9.394
5	6.728	9.771	15	7.417	9.653	25	6.773	9.606
6	7.181	9.147	16	6.839	9.618	26	7.011	9.688
7	6.758	9.371	17	6.892	9.724	27	6.737	9.524
8	6.737	9.206	18	6.722	9.512	28	6.887	9.347
9	7.063	9.594	19	6.835	9.571	29	7.063	9.634
10	6.811	9.501	20	6.782	9.447	30	6.912	9.406

The flow coefficient of the injector nozzle is calculated according to formula (1) [20]

$$\mu_f = \frac{Q_r}{Q_t} \tag{1}$$

(1) in the above formula, μ_f, Q_r and Q_t represent flow

coefficient, measured flow value and theoretical flow value respectively. The theoretical flow value is calculated according to formula (2).

$$Q_t = f_c \cdot \sqrt{\frac{2\Delta P}{\rho}} \quad (2)$$

(2) in the above formula, ΔP, ρ and f_c represent fixed pressure of the test, density of the test oil and total flow cross section of the spray hole respectively. The total flow cross section of the spray hole is calculated according to formula (3).

$$f_c = \frac{\pi}{4} d_0^{\ 2} \cdot i \quad (3)$$

(3) in the above formula, d_0 and i represent nozzle spray hole diameter and nozzle spray hole number respectively.

The tested nozzle is designed with eight spray holes and with the diameter of 0.45mm, importing the datum into the formula (3), the total flow cross section of the spray hole can get:

$$f_c = \frac{\pi}{4} \times 0.45^2 \times 8 = 1.2717mm^2$$

Assuming that $\Delta P = 10MPa$, $\rho = 0.84 \times 10^3 kg / m^3$, importing the datum into the formula (2), the nozzle theoretical flow value can get:

$$Q_t = 1.2717 \times \sqrt{\frac{2 \times 10}{0.84 \times 10^3}} = 0.1962L / S = 11.772L / Min$$

The flow coefficient before and after extrusion grinding can be obtained by importing the measured flow values before and after extrusion grinding and the theoretical flow value into the formula (1). The minimum and maximum values of the nozzle flow coefficient before and after extrusion grinding can be calculated correspond to the datum in Table 4. The specific calculative processes are as follow.

1. Before extrusion grinding

$$\mu_{f\min} = \frac{Q_{r\min}}{Q_t} = \frac{6.592}{11.772} = 0.56$$

$$\mu_{f\max} = \frac{Q_{r\max}}{Q_t} = \frac{7.417}{11.772} = 0.63$$

2. After extrusion grinding

$$\mu_{f\min} = \frac{Q_{r\min}}{Q_t} = \frac{9.147}{11.772} = 0.78$$

$$\mu_{f\max} = \frac{Q_{r\max}}{Q_t} = \frac{9.771}{11.772} = 0.83$$

The flow dispersion of the nozzle before and after extrusion grinding can be calculated correspond to the datum in Table 4. The specific calculative processes are as follow.

1. Before extrusion grinding

$$Q_b = \sum_{r=1}^{30} Q_r / 30 = 6.903$$

$$\delta_{上} = \frac{Q_{\max} - Q_b}{Q_b} \times 100\% = \frac{7.417 - 6.903}{6.903} \times 100\% = 7.4\%$$

$$\delta_{下} = \frac{Q_{min} - Q_b}{Q_b} \times 100\% = \frac{6.592 - 6.903}{6.903} \times 100\% = \text{-}4.5\%$$

2. After extrusion grinding

$$Q_b = \sum_{r=1}^{30} Q_r / 30 = 9.454$$

$$\delta_{上} = \frac{Q_{\max} - Q_b}{Q_b} \times 100\% = \frac{9.771 - 9.454}{9.454} \times 100\% = 3.4\%$$

$$\delta_{下} = \frac{Q_{min} - Q_b}{Q_b} \times 100\% = \frac{9.147 - 9.454}{9.454} \times 100\% = \text{-}3.2\%$$

Q_b, $\delta_{上}$ and $\delta_{下}$ above represent flow mean value, upper deviation and lower deviation respectively.

The calculation results of the liquid extrusion grinding in spray hole show that the flow coefficient was increased from 0.56~0.63 up to 0.78~0.83 and the flow dispersion was decreased from -0.4.5%~7.4% to -3.2%~3.4%. The flow coefficient increasing can effectively improve the spray quality and performance of the injection nozzle, and thus to improve the performance and exhaust emissions of the diesel engine. According to the GB/T 5772-2010, when the flow test is carried out on the high-pressure liquid flow test rig with 10MPa fixed pressure, the deviation rate between the maximum value and the arithmetic mean value of the nozzle flow should be no more than 6%, while the deviation rate between the minimum value and the arithmetic value of the nozzle flow should be no less than -6%, otherwise, the flow values should be grouped. The deviation rate between the maximum value and the calibration of the nozzle flow in the same group should be no more than 3%, while the deviation rate between the minimum value and the calibration of the nozzle flow in the same group should be no less than -3%. Although the flow deviation range of the nozzle after extrusion grinding was reduced significantly, but it still exceed the design target of ±2.5%, so it is necessary to group the flow values to ensure the performance of the diesel engine and prolong the nozzle assembly service life.

3.6. Bench Endurance Test

In order to verify the nozzle quality, we carried out the bench endurance test for 2000 hours in G8300ZD13 diesel engine. The structural parameters and performance indexes of the G8300ZD13 diesel engine are shown in Table 5, the technical parameters of the injector nozzle before and after bench endurance test are shown in Table 6.

Table 5. *Structural parameters and performance indexes of the G8300ZD13 diesel engine.*

Cylinder bore mm	Piston stroke mm	Compression ratio	Mean effective pressure MPa	Rated speed r/min	Specific fuel consumption g/KW.h
300	380	13	1.97	500	≤204

Table 6. *Technical parameters comparison before and after endurance test.*

NO.	Needle displacement (mm)		Tightness tests values (S)		Spray quality		Flow values (L/min)	
	Before test	After test	Before test	After test	Before test	After test	Before test	After test
1	0.51	0.52	5.5	5.1	qualified	qualified	9.382	9.522
2	0.50	0.52	5.8	5.3	qualified	qualified	9.501	9.693
3	0.50	0.51	5.6	5.2	qualified	qualified	9.418	9.598
4	0.51	0.53	6.1	5.5	qualified	qualified	9.406	9.656
5	0.51	0.52	6.0	5.7	qualified	qualified	9.394	9.624
6	0.52	0.53	5.7	5.4	qualified	qualified	9.447	9.697
7	0.50	0.52	5.9	5.4	qualified	qualified	9.385	9.615
8	0.51	0.52	5.6	5.1	qualified	qualified	9.512	9.742

The bench endurance test shown that the needle displacements, tightness tests values and flow values were little changed after the bench endurance test for 2000 hours, but they still meet the technical requirements of the part drawing, and the performance indexes of the G8300ZD13 diesel engine were not obviously change during bench endurance test. That is to say the nozzle performance is stable and reliable quality, the nozzle assembly service life should be longer in theory.

4. Conclusions

Metallographic structure, microhardness, retained austenite content, cooling chamber structure and spray holes liquid extrusion grinding which influenced the service life of the nozzle were investigated in this paper, with the following results:

Compared with the microstructures of the as-brazed and as-normalized 27SiMnMoVA steel nozzle, the as-normalized microstructures are appreciably finer than the as-brazed microstructures. The cryptocrystalline martensite was obtained under the heat treatment of austenitizing at 860°C for 1.5 hours and then quenching in 80°C hot-oil, which has better performance than that of the acicular martensite. The hardness gradient became much more smoothly and the carburized and hardened effective case depth of the nozzle seat increased from 0.48mm to 0.75mm after the carburized process added preheating period and diffusion period. The retained austenite contents decreased with the processes of decreasing subzero treatment temperature and prolonging subzero treatment time. Compared with the nozzle original cooling chamber structure, the volume increase rate and superficial area increase rate were increased by 13% and 23% respectively after improvement. The flow coefficient was increased from 0.56~0.63 up to 0.78~0.83 and the flow dispersion decreased from -0.4.5%~7.4% to -3.2%~3.4% by adopting liquid extrusion grinding, which basically meet the requirements of high performance diesel engine. The bench endurance test shown that the nozzle performance is stable and reliable quality, the nozzle assembly service life should be longer in theory.

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