A Method of Plasma Quenching in the Gun Barrel

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Abstract: In order to extend the service life of the barrel and improve its corrosion resistance and wear resistance, plasma quenching technology successfully processed the inner hole material. The treatment effect is obtained by making the analysis of the microstructure, hardness and tribological properties. The results show that the plasma quenching of the barrel material can form a martensitic hardening layer on the surface, when the surface hardness is increased by 725 HV, and the surface abrasion resistance is enhanced by 10 times. This technology provides a new way to extend the life of the barrel.

1. Introduction
At present, there are many anti-ablation and prolonged life measures for gun barrels\(^{1-2}\), but many problems exist. After the inner bore is plated with chromium, the chromium layer is mechanically bound up with the substrate, which cannot be metallurgically combined, so the anti-ablative ability is limited; the cost required for the magnetron sputtering bore is extremely high\(^{3}\); although the laser quenching technology can effectively improve the anti-ablative capability of the tube bore, its process is complicated and difficult to operate, and it has not been put into use\(^ {4}\).

In this paper, a new method for the life extension of artillery tubes is proposed, and it is the plasma surface hardening of the inner bore. The technical principle is to rapidly austenitize the inner wall by scanning the plasma beam with a higher energy density on the inner surface of the body tube, and then rapidly being cooled by the heat conduction of the tube itself to form a fine martensite structure on the inner surface, thereby increasing the surface hardness and wear and corrosion resistance\(^{5}\). The current plasma quenching equipment has been successfully applied to various workpieces and plasma torches have also been miniaturized. It is possible to quench tubes with internal diameters, greater than 35 mm, and the depth of the hardened layer is controllable, easy to adjust, and flexible\(^ {6}\). In this paper, the effect of plasma quenching technology on the structure, hardness and wear resistance of the pipe material is studied, and the effects of different plasma quenching parameters are also compared for providing reference for future engineering applications.

1.1 Selection of Test Materials
The adopted material was a cannon barrel of the Cannon Howitzer. The chemical composition is shown in Table 1. The wire was cut into 10 mm thick sheets, and the surface rust and oil stains were removed with a grinder, sandpaper and acetone prior to quenching. Finally, the wire was cut into a 50×10×10 mm sample with a roughness of 0.059 μm. In the friction and wear test, a ball-disk friction pair was employed. The grind piece was a GCr15 ball with a hardness of HRC 60, a roughness of 0.032 μm, and a diameter of 6 mm.
1.2 Test Equipment and Test Procedure
The authors entrusted Anhui Chenghe Technology Co., Ltd. with using its proprietary CHK-1 numerical control plasma beam multifunction surface processor to perform plasma surface hardening treatment on this sample. The process parameters are shown in Table 2. After quenching, a set of parameters was obtained. Surface roughness was measured with a JB-5C surface roughness profiler, mounted with a Struers cold inlay CitoVac, sanded and polished with the Struers high quality grinding and polishing system Tegramin-25, and etched with 4% nitric acid. After 15s, the tissue structure was observed under a Leica DM4M microscope; the surface and cross-sectional hardness were measured with a HV-1000IS Vickers micro-hardness tester, when the CFT-I multi-functional material surface performance tester was adopted for the friction and wear test. The test parameters are shown in Table 3. Finally, the sample was measured with a VK-X100K3D laser microscope, and meanwhile, the wear cross-sectional area and 3D topography of the ball friction pair are also discussed.

| Voltage | 90V |
|---------|-----|
| Electric current | 80~150A |
| The diameter of the nozzle | 6mm |
| Argon pressure | 0.5bar |
| Argon flow | 1.0(m^3h^{-1}) |
| Distance from the nozzle to the workpiece | 5mm |

| Speed | 300rpm |
| Loading | 20N |
| time | 30min |
| temperature | 23℃ |

2. Results and Analysis

2.1 Analysis on the Organizational Structure
Figure 1 shows the topography of a hardened zone after a 50-fold magnification of a quenched sample. The figure shows that the hardened area is in the shape of a crescent moon. The deepest point reaches 1.48mm. The interior of the crescent is a hardened zone of transformation, and the outer part is the material organization. Figure 2 shows the metallographic structure after plasma quenching. The figure shows that the plasma quenching can be divided into three areas according to the microscopic microstructure of the microstructure: (1) most parts of the surface are the hardened areas (Figure 2b), also known as the hardened areas, which are close to the surface and are therefore closest to the heat source with the highest temperature. In the quenched state, the holding time at the transformation point is the longest. In this case, the regional organization is completely converted to austenite. After quenching, the martensite structure was obtained, and the dislocation density was higher; (2)
transition zone appears between the hardened layer and the substrate (Fig. 2a). The main structures are martensite and sorbite. Compared with the hardened area, although the cooling rate is fast, due to the low temperature, there is no sufficient austenitization, and the carbides are not dissolved enough, resulting in a low content of martensite. As the quenching power increases, the area will also diffuse toward the substrate; (3) the interior is the matrix zone, while the main organization is sorbite, when this layer failed to reach the phase transition temperature. In this case, no tissue changes were seen, and only the original tissue appears.

![Fig. 1 Quenching Zone Morphology](image1)

**Fig. 1 Quenching Zone Morphology**

![a The Transitional Region of the Microstructure(X200) b The Hardened Region of the Microstructure(X1000)](image2)

**Fig. 2 The Microstructure after Plasma Hardening**

### 2.2 Hardness Testing and Analysis after Quenching

After plasma quenching, the surface hardness of the specimen is tested. The test method was to average the measurements 5 times in the direction perpendicular to the quenched strip at the surface of the specimen. The results showed that the surface hardness increased from the original of about 320 HV to about 725 HV. Then, it can be found that plasma quenching can effectively increase the surface hardness of gun steel materials, due to the fact that plasma quenching is a process of rapid quenching. The heating is rapid; the austenite grains are ultra-fine; the carbon is less uniform in austenite, and the carbon content in the formed martensite is also relatively high, so that the surface possesses higher hardness.
After the plasma quenching, the cross-sectional hardness of the test specimen was measured. The method tended to measure three types of hardness in every 100 μm from the surface quenching center and take the average as the hardness of the layer until the position of the matrix material. The hardness change curve with the depth is shown in Figure 3. The following conclusions are drawn from the figure: (1) the hardness distribution in the hardened layer is uniform, and there is no significant drop in the gradient, when it is one of the differences between plasma quenching and conventional quenching. According to this characteristic, it can be inferred that even if the surface is abraded during the launch of the artillery, the contact surface of the new layer can still maintain a high hardness value, and the wear resistance can be kept. Therefore, the life of the tube can be guaranteed, and will be extended to a great extent; (2) there is no obvious transition zone between the hardened zone and the matrix, and the hardness shows a sharp drop; (3) the maximum value of the hardness is not at the top surface but at the subsurface layer. The explanation from the perspective of heat transfer is that the hardness depends mainly on the cooling rate. Since the outermost surface layer of the quenching head will contact the air after the plasma jet moves, air quenching will occur, when it is not strong enough, and there is no effect of quenching and rapid heating, which makes partial austenite transformation insufficient; the subsurface layer cools fast during the process of cooling down, and the organization transformation is complete. Therefore, it possesses the highest hardness. In the transition zone between the crescent and the substrate, although the cooling rate is the fastest and the temperature in the area is not high enough, the structure is not fully austenitized and the hardness is also low.

2.3 Characteristics of the Friction Coefficient in the Hardened Zone

Figure 4 shows the curve of the friction coefficient over time between the quenched specimen and the original specimen. The results show that: (1) when the steady state is reached, the surface friction coefficient of the quenched specimen is lower than that of the unquenched specimen. In this case, it is believed that the plasma quenching can effectively enhance the friction and wear properties of the pipe material and reduce the friction coefficient; (2) the friction coefficient of the quenched specimen after stabilization is 0.90, while the friction coefficient of the original specimen is 1.16, which is a 22.4% reduction when compared with the original condition, because the plasma quenching makes the surface of the gun barrel material a hardened layer. Compared with the hardness of the substrate material, it is featured with a functional hardness gradient and better wear resistance. During wear, the load is carried by the hardened layer, so that the shear force acts on the surface, which effectively reduces the friction coefficient. At the same time, the high-hardness quenched layer on the surface of the material suppresses the generation of adhesive wear, which also makes the friction coefficient smaller after plasma quenching. The surface of the unquenched sample, due to the cutting action of the GCr15 ball, was torn since the surface was rough, and the coefficient of friction was high.
2.4 Wear Area and Wear Profile Analysis

In Figure 5, the wear cross-sectional area of quenched specimens is compared with the original.
specimens. It can be found that the depth and the width of the wear scar concerning the original sample are significantly larger, and there is a deep groove mark along the rubbing direction on the surface of the material, resulting from the plowing effect. The original sample wear cross-sectional area was 57752.10um², and the quenched sample was 4462.92um². Then, it can be seen that the wear cross-sectional area of the gun steel after plasma quenching is significantly less than that of the unquenched specimen, which is about one eleventh of the unquenched specimen. From FIG. 6, it can be found that the worn surface of the steel ball also has a groove mark due to the effect of the furrow, and a part of the wear scar is convex, caused by the loading and unloading of the steel ball during the wear process. Metal flow occurs on the surface of the contact point, and severe plastic deformation also appears. The resulting adhesive joints are sheared in the direction of motion because the action of shear forces causes the wear debris to migrate from one surface to the other, when resulting in severe adhesive wear. With the progress of friction and wear, the kinetic energy of the tester is transformed into thermal energy at the contact point. The plastic deformation of the substrate increases with the increase of the friction surface’s temperature, and the peeling pit is formed on the surface of the substrate. When compared with other samples, it can be seen that the blasted steel material after the plasma quenching becomes lighter, resists ploughing and possesses a relatively flat surface. It is also proved that the plasma quenching treatment reduces the wear of the gun steel material, and only a small amount of wear debris is presented at the wear scar. The wear mechanism is known as abrasive wear. At the same time, the high hardness quenched layer on the surface of the material inhibits the generation of adhesive wear, when at the same time, the surface is relatively smooth.

3. Conclusion
1. The surface of the original body tube is a coarse sorbite body. After plasma quenching, the structure becomes fine martensite. After quenching, the microstructure is divided into three layers from the surface to the inside. The thickness of the hardened layer closest to the surface is 1.48 mm, which is the deepest point in this test. Therefore, it can be seen that the plasma strengthening method can improve the organizational form of the tube material.
2. After the plasma quenching, the surface hardness of the barrel is increased from the original of about 320HV to the highest 750HV. In this case, it can be considered that the plasma quenching technology effectively increases the hardness of the gun steel and prolongs the service life of the gun.
3. After the plasma quenching, the friction coefficient of the material decreases by 22.4%. The wear cross-sectional area of the quenched specimen is obviously smaller than that of the unquenched specimen, which is about one eleventh. Therefore, the surface wear resistance is increased by 11 times, and the wear mechanism changes from sticky wear to abrasive wear.
4. This test mainly proves the applicability of the technology in the field of life extension management, and the obtained parameters have a certain reference value.

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