Research on tribological properties of H13 steel of shield machine hob by laser shot peening

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Abstract
In this paper, the laser shot peening (LSP) technology of H13 steel is studied to improve the friction and wear performance of shield machine hob. And to utilize the LSP experiment and simulation analysis, the influence of LSP parameters on the friction and wear performance of H13 steel after strengthening is studied. The numerical simulation study reveals the variation law of laser parameters on residual stress and stress layer depth. Study on friction and wear characteristics of H13 steel after LSP. The results show that the maximum residual stress of H13 steel is 911 MPa, and the hardness is 650.7 HV, when there are three times of black paint absorption and LSP. Compared with the raw material, the residual stress is increased by 125%, and the hardness is increased by 18%. And its friction coefficients and wear volume were relatively lower than other schemes. The average friction coefficient and wear volume were reduced by 10.8% and 57.2% respectively.

Keywords Laser shot peening · Simulation · Tribological properties

1 Introduction
The cutter ring of the shield machine is the key part of the shield machine, and it is also the most easily worn part in the working process. At present, H13 steel is mainly used to manufacture the cutter ring of shield machine. Telasang et al. [1] deems H13 steel has high toughness, hardenability, cold and hot fatigue resistance and is not easy to produce hot fatigue cracks. However, Ren et al. [2] analyzed that the cutter made of H13 steel has some defects such as eccentric wear, fracture, and wear. Wu et al. [3] summarized a variety of advanced processing technologies such as laser processing and machining to change surface characteristics and improve material tribological properties. At present, the main strengthening methods of H13 steel are laser surface strengthening, and Jia et al. [4] through laser surface melting strengthened the H13 steel. Dadoo et al. [5] used TiC composite coating to strengthen the surface hardness and the surface additive strengthening. Yang et al. [6] and Liu et al. [7] respectively have used the boronizing and nitriding to strengthen the H13, so these are also commonly used for surface strengthening of H13 steel. Hu et al. [8] deem that LSP is a kind of surface modification technology using short pulse laser beam. The LSP on 7075-aluminum alloy surface was studied by Wang et al. [9]. The authors concluded that LSP is an effective approach to decrease the depth and width of wear scars, and to reduce the abrasion loss in seawater environment. These observations were attributed to the grain refinement during LSP which increases the surface hardness and abrasion resistance. Ren et al. [10] researched laser shock peening to reveal the effects on Cr12 microstructures and fatigue resistance. These results show a deep layer of compressive residual stress is developed by laser shock peening by Angulo et al. [11], and ultimately, the isothermal stress-controlled fatigue behavior is enhanced significantly. Kyun et al. [12] through shot peening H13 steel improved the hardness and residual compressive stress. The residual compressive stress increases, and the toughness of the material increases.

Through the above research by all researchers, LSP technology has not been applied to H13 steel of shield machine.
hob. Research on tribological properties of H13 steel of shield machine hob by LSP has great significance to the study of LSP to strengthen high load tools.

2 Simulation model

2.1 Material model

The material H13 steel used in the experiment is medium carbon steel. After quenching 1313 K and secondary tempering 853 K, the material performance is the best. And the performance parameters are shown in Table 1.

LSP simulation is dynamic analysis, so the J-C constitutive model of H13 steel is used. The J-C constitutive model parameters are shown in Table 2.

The size of specimen is 40 mm × 40 mm × 15 mm. The hardness is about 550 HV, and the residual compressive stress is 420 MPa.

2.2 Pressure model of laser shot peening

Lu et al. [13] has explained the theory of LSP. High-energy laser beams pass through the confinement layer of the material surface and irradiate the absorption layer of the material. After absorbing a lot of laser energy, high-pressure plasma will be produced. Due to the existence of the confinement layer, the plasma forms stress waves. Under the action of stress wave, plastic deformation occurs. Meantime, the near surface microstructure of the material has refined by the stress wave, and the compressive stress is produced. The hardness of material would increase, as the result of microstructure was refined. The theory of LSP is shown in Fig. 1.

When the laser-induced wave propagates in the target, the peak pressure (P) of the LSP exceeds the Hugoniot Elastic Limit (HEL) of the target, and the plastic deformation of the target surface occurs [14]. HEL estimation mathematical formula:

\[ HEL = \sigma_Y^D \frac{1 - \nu}{1 - 2\nu} \]

where \( \sigma_Y^D \) is the tensile strength; \( \nu \) is Poisson’s ratio. Substituting the parameters into the solution: HEL (H13) = 4093 MPa. When \( P_{\text{max}} = 2 \sim 2.5 \text{ HEL} \), the material has permanent deformation in the study of Shukla et al. [15]. The laser pulse width is 20 ns, and the pressure model of LSP is shown in Fig. 2. The simulation model of LSP is shown in Fig. 3.

3 Experimental design

3.1 Theory of laser shot peening

LSP is a transient process, so it is impossible to accurately experiment and calculate the pressure produced by laser beam impacting the target. In order to estimate the pressure produced by shock wave, Fabbro et al. [16] have proposed a formula for estimating the peak pressure of shock wave on the target surface.

\[ P = 0.01 \sqrt{\frac{a}{2\alpha + 3}} \sqrt{Z\sqrt{I_0}} \]

where \( a \) is the ratio of thermal to internal energy, when the black paint is absorption layer, which is 0.3. The acoustic impedance of water is \( 2.39 \times 10^5 \text{ g/cm}^2 \cdot \text{s} \). The acoustic impedance of H13 steel is \( 45.8 \times 10^5 \text{ g/cm}^2 \cdot \text{s} \).

\( Z \) represents the total impedance of the constraint layer and the target material, which is determined by the constituent layer impedance \( (Z_{\text{overlay}}) \) and the target impedance \( (Z_{\text{target}}) \) together:

\[ \frac{2}{Z} = \frac{1}{Z_{\text{overlay}}} + \frac{1}{Z_{\text{target}}} \]

\( I_0 \) represents laser power density:

\[ I_0 = \sqrt{\frac{E}{\pi d^2 \tau}} \]

\( E \) is the laser pulse energy. \( d \) is laser spot diameter, and \( \tau \) is laser pulse width.
3.2 Experimental scheme

LSP equipment (YS80-R200B, XA, SN, CHN) was used for LSP treatment, and the LSP parameters are shown in the Table 3. The processing path of LSP is shown in Fig. 4.

After LSP, the sliding friction and wear behaviors between H13 steel and GCr15 bearing steel (the diameter of 6.35 mm, the hardness of 750 HV) under different pressures were studied by RTEC multifunctional friction and wear tester (MFT-50, San-Jose, CA, USA). The schematic diagram of friction and wear tester is shown in Fig. 5. The experimental parameters are as follows: load 75 N and 100 N (the pressure ranges from 300 to 400 MPa), amplitude 4.5 mm, frequency 4 Hz, time 60 min. The friction coefficient and the experimental temperature were monitored in real time by the matching program of the testing machine. The wear profile and wear volume were measured by USP sigma white light interferometer (USP-Sigma, Saint Louis, MO, USA). The morphology of wear mark, residual stress, and hardness were observed by X-ray stress meter (iXRDCOMBO, Proro, Canada) and micro-Vickers hardness meter (402-MVD, Wilson, Norwood, USA).

4 Result and discussion

4.1 Simulation result

The simulation analysis uses ABAQUS software. Firstly, the dynamic response of H13 steel model under LSP was analyzed in the display integration module, and then the static rebound was carried out in the implicit integration module. In case of multiple LSP, the interval static rebound time is the interval time of machining. The final rebound time is 1000 times of the dynamic response time, which makes the material fully rebound.

In Fig. 6a, the trend of residual stress of H13 steel is studied by changing the pressure and times of LSP wave. When the pressure increases from 4 to 12 GPa by LSP once, the maximum residual pressure stress and the maximum residual tensile stress show an increasing trend. The
pressure stress increases from $-472$ to $-1204$ MPa, and the tensile stress increases from $111.7$ to $690.4$ MPa. Figure 6b shows the residual strain corresponding to LSP once. With the increase of shock pressure, the strain increases from 0.013 to 0.139. When the three-times LSP pressure increases from 4 to 12 GPa, the maximum residual pressure stress and the maximum residual tensile stress show an increasing trend. The pressure stress increases from $-744.7$ to $-1652$ MPa, and the tensile stress increases from $190.8$ to $1019$ MPa. Figure 6b also shows the residual strain corresponding to three times of LSP. With the increase of LSP pressure, the strain increases from 0.033 to 0.436. It can be concluded that the residual stress and strain increase with the increase of LSP pressure.

However, H13 steel shows 420 MPa residual pressure stress, when the LSP residual tensile stress is greater than 420 MPa, the specimen will have residual tensile stress, and the occurrence of participating tensile stress will lead to cracks in the material. Therefore, in the LSP simulation, the LSP pressure cannot be greater than 8 GPa (residual tensile stress is 441.6 MPa) in once and 7 GPa (residual tensile stress is 461.8 MPa) in three times.

Figure 7 has shown the residual stress and strain of different LSP pressure. It can be seen that with the increase of LSP pressure, the influence layer of residual stress increases by about 0.2 mm. With the same residual stress, the deeper the stress layer, the stronger the LSP toughness. In Fig. 7a, the residual stresses of LSP three times by 6 GPa have approximately equaled to the LSP once by 8 GPa. The pressure layer of LSP once by 8 GPa is about 0.4 mm deeper than LSP three times by 6 GPa. Its strain is about 0.02, and it is smaller than LSP three-times by 6 GPa from Fig. 7b. When it maintains the same LSP pressure, with the LSP times increase, the residual stress and stress layer increase. Therefore, it can be concluded that the LSP pressure is larger and the pressure layer is deeper at one time. The residual stress is larger and the stress layer is deeper at three-times.

### 4.2 Experimental result

The residual stress increases with the increase of LSP pressure. Excessive residual stress is easy to cause cracks and reduce the service performance. In order to obtain large residual stress without crack, the required laser energy and spot size are calculated with 6 GPa as LSP pressure. After LSP processing, the surface morphology of the material as shown in Fig. 8a–d, respectively, corresponds to the raw material, once LSP by black paint absorption, three-times LSP by black paint absorption, and three-times LSP of no absorption. It can be seen that the deformation of specimen (c) is larger than the others.

![Fig. 4 The processing path of LSP](image)

![Fig. 5 The schematic diagram of friction and wear tester](image)
Fig. 6 Residual stress and strain trend of LSP simulation: a residual stress; b strain

Fig. 7 Residual stress and strain of different LSP pressure: a residual stress; b strain

Fig. 8 Surface morphology: a surface morphology of raw material; b surface morphology of black paint absorption LSP once; c surface morphology of black paint absorption LSP three-times; d surface morphology of no absorption LSP three-times
4.2.1 Microhardness

The hardness of the material was tested by microhardness tester. The hardness of the surface was randomly taken from 15 points, and the average hardness was obtained by removing the maximum value and the minimum value. In Fig. 9a, the a, b, c, and d respectively correspond to the raw material, once LSP by black paint absorption, three-times LSP by black paint absorption, and three-times LSP of no absorption, where hardness is about 550 HV, 616 HV, 650.7 HV, and 629.36 HV respectively. Compared with the hardness, it can be concluded that the strengthening effect is the best when the black paint absorption and LSP for three-times; the hardness is increased by 100.7 HV, and the strengthening effect is about 20.13%. In terms of hardness, the scheme of three-times LSP of black paint absorption is the best.

4.2.2 Residual stress

The residual stress of the material was measured by X-ray stress measuring instrument. The residual stress of 15 points was randomly selected on the surface. In Fig. 9b, the a, b, c, and d respectively correspond to the raw material, once LSP by black paint absorption, three-times LSP by black paint absorption, and three-times LSP of no absorption. According to Fig. 9b, the residual compressive stress of a is 420 MPa. The residual compressive stress of c is the largest, about 911 MPa. The residual stresses of b and c are approximately equal. The residual stress and simulation stress of c combined with the residual stress of a can be obtained that the experiment and simulation results are approximately equal. b is the once LSP; its residual stress layer of the specimen is small, and the maximum residual stress appears near the surface layer. The residual stress measured by X-ray residual stress measuring instrument is the maximum residual stress of the material, which is equivalent to the simulation. However, the residual stress of d is quite different from the simulation results. The reduction of the residual compressive stress in d is due to the annealing effect of high-energy laser irradiation on the sample without absorption layer. From the aspect of residual stress, the scheme of three-times LSP with black paint absorption (c) is the best.

4.2.3 Friction coefficient

Average friction coefficient After LSP to strengthen H13 steel, the friction experiments were carried out by the friction and wear testing machine. Each experiment parameter is repeated three-times to obtain the stable friction coefficient and calculate the average friction coefficient. Figure 10a shows the average friction coefficient of the raw material, once LSP by black paint absorption, three-times LSP by black paint absorption, and three-times LSP of no absorption. And the initial pressure is 75 N and 100 N in fiction. When the initial pressure is 75 N, the friction coefficient of black paint absorption LSP three-times is 0.4091 that is the lowest, and the raw material is 0.4601. The results are consistent with the trend of hardness. The reason for this phenomenon is the high hardness of material and relative fine grains. And when the initial pressure is 100 N, the friction coefficients increase, but the trend is consistent with the hardness. The reason for the increase in friction coefficient is that when the initial pressure increases, the friction type and wear morphology of the experiment piece change.
Friction coefficient

Figure 10b shows friction coefficient of the friction process. In the friction process, except for early fluctuations, the overall trend is the same as that of hardness. As the friction zone enters the bottom layer of the point region, the hardness of the material in this region is uniform, and the friction coefficient tends to be stable. After initial fluctuation, the friction coefficient is stable at 0.4215. Because of the black paint absorption LSP once, the surface hardness of the sample is low, and the friction coefficient is large. At the same time, the wear gradually approaches the strengthening area near the surface layer, where the strengthening points overlap more times, the friction coefficient is lower, and the wear type does not change when the initial pressure is 75 N. Therefore, the general trend of the friction coefficient of the sample black paint absorption LSP once by 75 N shows that it fluctuates and decreases, and finally tends to be stable.

Figure 10b shows friction coefficient of the friction process. In the friction process, the overall trend is the same as that of hardness, except for the early fluctuation. When the initial pressure is 75 N, after the friction coefficient is stable, there is a big fluctuation of black paint absorption LSP once, because of the lower surface hardness. And its main strengthening layer is near the surface layer; the friction coefficient is low in the area where the number of strengthening spot overlaps is more. After the initial fluctuation, the friction coefficient is stable at 0.4215. Because the friction area enters into the bottom layer of the spot area, the material hardness in this area is uniform, and the friction coefficient tends to be stable.

However, when the initial pressure is 100 N, this phenomenon does not appear. This is because the initial pressure increases, and the friction process enters the near surface area with uniform hardness quickly. Therefore, when the initial pressure is 100 N, the friction coefficient curves fluctuate slightly. From Fig. 10b, it can be seen that when the initial pressure is 75 N, compared with the initial pressure of 100 N, the friction coefficient is lower, and the trend is the same as the average friction coefficient.

4.2.4 Wear morphology

Macromorphology by white light interference Wear morphology was observed by white light interferometer, and wear volume was calculated. Figure 11 shows the wear morphology and wear volume of under the 75 N and 100 N. Figure 11a shows wear morphology of raw materials. The wear surface is rough and has large lumps. The reason for this phenomenon is that the hardness of the material is relatively low, and the flake will fall off under high load friction. In Fig. 11b, c, the depth of wear mark after LSP once is lower than that of three-times with black paint absorption layer. Moreover, there are more furrows in the wear morphology after LSP once. When the impact times are the same, the depth of wear mark with black paint absorption is lower than that with no absorption. In Fig. 11i, the regularity of wear volume is the same as that of friction coefficient. This shows that the hardness increases, but the friction coefficient and wear volume decrease. When the initial load is 100 N, the regularity of wear morphology is the same as that of 75 N. As shown in Fig. 11i, the wear volume increases with the increase of initial pressure.
Micromorphology by SEM The wear morphology was observed by SEM. There are some oxides and carbides in the wear marks. Due to the deep wear marks, the material oxidizes to form iron oxide. Carbide is mainly the material, and the hard phase in the grinding ball falls off and is rolled into the wear mark by the grinding ball. In Fig. 12a, there are mainly flake shedding and microcutting marks in the wear morphology. In Fig. 12b, in addition to flake shedding, there are furrows and squashed abrasives in the wear morphology. The detached abrasive grains form three-body wear with the worn parts, thus forming furrow. At the same time, the exfoliated abrasive particles are rolled into the worn surface by GCr15 to form squashed abrasives. In Fig. 12b, the wear mark surface is mainly microcutting, furrows, and abrasives. There are only some carbides in the wear marks. And the wear mark surface of LSP three-times no absorption is mainly microcutting and a small amount of shedding. As the initial pressure increases, the quality of wear morphology decreases. As shown in Fig. 12 e, f, g, and h, the wear morphology has showed massive flakes. Due to the increase of load, there are more adhesive wear in the friction type, resulting in a large number of surface shedding. This is also the reason why the friction coefficient increases with increasing load.

The wear morphology was observed by SEM. There are some oxides and carbides in the wear marks. Due to the deep wear marks and the increase of temperature in the friction process, oxidative wear occurs on the wear mark surface, and the material oxidizes to form iron oxide. Carbide is mainly the material, and the hard phase in the grinding ball falls off and is rolled into the wear mark by the grinding ball.
Fig. 12 Wear micromorphology: a wear morphology of raw material by 75 N; b wear morphology of black paint absorption LSP once by 75 N; c wear morphology of black paint absorption LSP three-times by 75 N; d wear morphology of no absorption LSP three-times by 75 N; e wear morphology of raw material by 100 N; f wear morphology of black paint absorption LSP once by 100 N; g wear morphology of black paint absorption LSP three-times by 100 N; h wear morphology of no absorption LSP three-times by 100 N
In Fig. 12a, there are mainly flake shedding and microcutting marks in the wear morphology. In Fig. 12b, in addition to flake shedding, there are furrows and squashed abrasives in the wear morphology. Different from the raw materials, the wear marks of LSP samples are reduced due to the increase of hardness. The phenomenon of peeling oxide layer exists, and the peeling oxide layer is rolled to the wear surface by GCr15, forming crushing abrasive. The oxide layer, which is not completely exfoliated, is separated in the process of friction, resulting in three-body wear between abrasive particles and worn parts, thus forming grooves. In Fig. 12b, the wear mark surface is mainly microcutting, furrows, and abrasives. And the wear mark surface of LSP three-times no absorption is mainly microcutting and a small amount of shedding. Therefore, when the initial pressure is low, abrasive wear is dominant, and oxidation wear is accompanied in the wear marks. As the initial pressure increases, the quality of wear morphology decreases. As shown in Fig. 12e–h, the wear morphology has shown massive flakes. Due to the increase of load, there are more adhesive wear in the friction type, resulting in a large number of surface shedding. This is also the reason why the friction coefficient increases with increasing load.

4.3 Analysis and discussion

Through simulation and experiment, it is found that the hardness and residual stress of the H13 steel after three-times of LSP are higher than that of once LSP. This is due to the plastic deformation caused by high-pressure shock wave and the increase of dislocation density caused by shock wave, resulting in grain refinement. Meantime, the effect of black paint absorption is better, especially the residual stress. In the aspect of friction coefficient, for the H13 steel with good strengthening effect, the friction coefficient is relatively low. And the early running in wear stage is relatively short. The friction coefficient is related to the surface quality and material properties of the friction pair, but not to the applied load. However, the friction coefficient is increased by 100 N. Through SEM, when the initial pressure is 100 N, there are more flakes that appeared on the surface. The reason for this phenomenon is that as the load increases, the heat generated during the friction process also increases. And the wear type changes from simple abrasive wear to composite wear. The composite wear mainly includes abrasive wear and adhesive wear. The change of wear type, especially the appearance of adhesive wear, directly leads to the deterioration of the friction pair surface, thereby increasing the friction coefficient.

5 Conclusion

1. The results of LSP simulation show that the residual stress and the stress layer increase with the increase of LSP times and LSP pressure. In order to select the best experimental parameters, the LSP strengthening simulation is combined with the properties of raw materials. The residual stress of H13 steel is ~420 MPa. Combined with the simulation, the optimal range of LSP pressure is 6–7 GPa.
2. The results show that the residual stress of H13 is decreased after LSP without absorption layer. LSP without absorption layer absorbs laser energy, resulting in annealing of H13 surface and reduction of residual compressive stress.
3. The LSP treatment shows that with the LSP times increase, the residual stress and the hardness increase. When the energy is 7 J, the spot diameter is 2.4 mm, and the LSP is 3 times; the residual stress and the hardness are the largest. Through the friction and wear experiment, it is found that the hardness increases, and the friction coefficient and the wear volume decrease. The increase in friction load will not directly lead to an increase in friction coefficient. However, as the load increases, the type of wear shows adhesive wear, so the friction coefficient increases.

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Availability of data and material The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval This article meets the ethical standards: (1) there is no potential conflict of interest; (2) studies that do not involve human participants or animals; (3) the submissions have obtained the informed consent of all authors.
Consent to participate  The authors declare their approval to participate in the submitted manuscript.

Consent for publication  All the authors have read and agreed to the published version of the manuscript.

Conflict of interest  The authors declare no competing interests.

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