Determination of the optimal coverage for heavy-duty-axle gears in shot peening

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Abstract
Pitting and wear often appear on heavy-duty-axle gears due to their harsh working conditions, such as high torques, high loads, and poor lubrication. Shot peening is a popular surface strengthening method for gears. In order to ensure complete coverage during shot peening, 100~200% coverage is usually prescribed for most gears. However, it is difficult to effectively improve the contact fatigue and wear resistance of heavy-duty-axle gears. Generally, increasing shot peening coverage can heighten the compressive residual stress for prolonging the service lifetime of gears, whereas high coverage levels may cause the deterioration of surface roughness, thus increasing the noise and vibration of gears. To address this issue, this paper deals with the determination of optimal coverage for heavy-duty-axle gears by experimental tests. The influence of shot peening coverage on the surface integrity of gears is analyzed in terms of residual stress, microhardness, surface morphology, and microstructure. The results show that the maximum compressive residual stress increases first and then keeps stable with the increase of coverage, and the maximum value is $-1172.10$ MPa. The microhardness peak increases obviously in the beginning and then slowly rises with the increase of coverage, and the maximum value is $747.5$ HV 1.0. The surface roughness ($R_a$) decreases initially and then enhances with the increase of coverage, and the minimum value is $0.99$ $\mu$m under the coverage of 1000%. The crystallite size can be refined from 36.88 to 28.79 nm by shot peening. The dislocation density increases with the increase of coverage, and the maximum value is $3.70 \times 10^{16}$ m$^{-2}$. Numerous damages (microscalings, spallings) occur on the treated gear tooth flank affecting the residual stress distribution and roughness under high coverage levels. Meanwhile, the wear behavior of gear steels is investigated, and the wear test results show that shot peening with the coverage of 1000% can lead to a better wear resistance. Taking into consideration of surface integrity and wear test results, the coverage of 1000% is the optimal coverage for heavy-duty-axle gears in shot peening.

Keywords Shot peening · Heavy-duty-axle gear · The optimal coverage · Surface integrity

1 Introduction
Spiral bevel gears mounted on the drive axle are key transmission parts for heavy-duty vehicles. The meshing gear pair suffers from percussive load, high torque, and harsh running conditions; thus, initial pitting and wear failures often occur on the gear tooth flanks $[1, 2]$. Shot peening is a cold working process, wherein a lot of shots with high hardness and high speed strike the surface of the workpiece and induce compressive residual stress for the improvement of the anti-fatigue performance of the workpiece $[3]$. It is a common gear surface strengthening method and is usually combined with heat treatment processes in the process of gear manufacturing like carburization, nitridation, and nitrocementation. Typically, the load-carrying capacity of a gear can be increased by 20 to 30% after shot peening $[4]$. More importantly, without increasing the size and weight of the gear or changing novel materials, designers can improve the fatigue strength of the gear through shot peening, so it can reduce manufacturing cost and improve fuel efficiency from the aspect of economy and ecology $[5]$. In addition, shot peening can (1) induce tiny...
indentations on the tooth flank as very small oil reservoirs which help to promote lubrication, reduce wear, spalling, scoring, and lower operating temperature by reducing friction [6–9]; (2) eliminate the tool marks left by machining and reduce the stress concentration on gear tooth flanks [10]; and (3) reduce surface abnormal layer [11]. Therefore, shot peening is such a process that can improve the fatigue strength and load-carry capacity of gears, and can meet the requirements of the lightweight design of gears.

Coverage is one of the most important parameters in the shot peening process, and other parameters such as shot peening intensity, shot peening pressure, mass flow rate, shot size, impact angle, and distance from nozzle to workpiece are all related to it. Coverage is defined as the percentage of a given surface area actually impacted by shot peening (dimpled surface) [12]. It is proportional to shot peening time [13]. Coverage beyond 100% (i.e., 200%, 300%) is defined as multiples of the time taken to achieve 100% coverage (i.e., 2×, 3×) [14]. There are some methods to verify the coverage of peened gears [14, 15], including fluorescent tracer dyes, optical analyzers, dye marker inks, etc. Considering production cost, processing efficiency, and shot wear, manufacturers usually select 100% or 200% coverage to ensure uniform injection of gears. However, they rarely pay attention to the effect of higher coverage levels on gears. For the maximum improvement of fatigue and wear resistance of gears, 100–200% coverage may not be the optimum value. Different materials and shapes of parts have their most appropriate coverage, so reasonable selection and control coverage levels can achieve the best shot peening effect [16].

Most of the changes in surface integrity of workpieces induced by shot peening may affect the success of the treatment. Shot peening coverage has great effects on the surface integrity of workpieces. Wu et al. [17] investigated the effect of shot peening with 100% and 200% coverage on the hardness, residual stress, and grain size for 18CrNiMo7-6 carburized gear steel. Maleki et al. [18] studied the effect of shot peening coverage on properties of AISI 1045 carbon steel, of which the shot intensity was 27A, and the coverage was 100%, 500%, 1000%, and 1500%, respectively. The results indicated that compressive residual stress distribution was increased slightly with coverage, whereas the amount of grain refinement was directly related to coverage. Microhardness of the peened workpiece in high coverage was significantly increased, and the surface roughness enhanced with the increase of coverage until reached a stable value. Whereafter, Maleki et al. [19] detected the influence of coverage on hardness, grain size, and residual stress of AISI 1060 steel by an orthogonal test. The results indicated that the weight values of coverage affecting microhardness, grain size, and residual stress were 68%, 89%, and 57%, respectively. Inoue et al. [20] found that for SCM415 spur gears, the surface hardness of tooth root could increase 30–80 HV with the increase of shot peening coverage (150–600%) and intensity (0.25–0.85 mmA), and the coverage had little influence on the residual compressive stress near the gear root. However, the coverage variation range is not wide in Inoue’s study. Santa-aho et al. [10] studied the effect of shot peening on the tooth surface roughness of 17NiCrMo6-4 carburized gear through a scanning electron microscope (SEM) characterization experiment. The results showed that increasing shot peening intensity and coverage density at the same time could reduce the surface roughness when gears were harder than the shots used in the experiment. Based on the review of many researchers’ studies, previous studies mainly focus on gear steels and spur gear roots. The failure mechanism for tooth flanks and tooth roots is different, and the key surface integrity parameters differ from tooth roots and flanks. Thus, it is indispensable to investigate the surface integrity of gear flanks under different coverage. More importantly, the machining methods for spiral bevel gears (i.e., face hobbing or face milling) result in a different surface integrity after peening. Furthermore, the study on surface integrity of gears or gear steels treated by shot peening is incomprehensive, such as the evolutionary mechanism of microstructure. In particular, the quantitative analysis of the microstrain and dislocation density on the gear tooth flank after shot peening is rarely reported. And then, the understanding of the effects of coverage on residual stress distributions is still not clear, and sometimes, it exists some debatable results as shown in refs. [17, 18, 20–22]. Finally, the investigation scope of shot peening coverage on surface integrity of gears is not wide, and especially, high coverage levels which may cause different kinds of surface defects should be considered.

Aiming to determine the optimal coverage for heavy-duty-axle gears in shot peening, the effect of shot peening coverage on surface integrity of gear tooth flanks is investigated by experimental characterization. A wide range of coverage levels (100%, 500%, 1000%, 2000%, 4000%) are selected in this research. The investigated surface integrity parameters include residual stress distribution, microhardness, surface roughness, microtopography, crystallite size, dislocation density, etc. Wear tests are performed to analyze the wear behavior of gear steels to verify the optimal shot peening coverage. The research has high engineering value for shot-peening parameter selection to improve contact fatigue and wear resistance of gears.

2 Experiment setup

2.1 Material and specimens

The subject of the research is spiral bevel gears mounted on heavy-duty axles, and 5 specimens are processed in the same batch made of 22CrMoH gear steels. The measured chemical
composition of the steel is tabulated in Table 1. The gear module and tooth number for each specimen are 10.345 mm and 24, respectively. As shown in Fig. 1, the processing of the test gears is mainly divided into the following stages: forging, normalizing, face hobbing, heat treatment, shot peening. Thereinto, the heat treatment process consists of carburizing, quenching, and low-temperature tempering. Then, the gears have an effective case depth (depth to 550 HV) of about 1.7 mm; the surface hardness and core hardness are about 59–64 HRC and 33–45 HRC, respectively.

### 2.2 Shot peening treatment

The shot peening experiment is performed with automatic compressed air shot peening equipment (Liangshi, LSSKWPWP-8). The gear specimen for each test is fixed on the worktable and rotates with its own central axis under the jet stream. The nozzle moves along the root cone of the gear. Each station of the machine is equipped with 4 nozzles and 4 nozzles with a slight offset process a gear simultaneously. The inner diameter of the nozzle is 8 mm, the moving speed of the nozzle is 3 mm/s, and the distance from the nozzle to the workpiece is controlled as 150 mm. For the complex gear shapes, the impact angle and worktable rotational speed are set as 50° and 25 r/min, respectively. The shot peening pressure is set as 0.45 MPa, and the mass flow rate is set as 13 kg/min. Thus, the shot velocity is controlled by adjusting shot peening pressure and feed valve setting. The shot peening process is shown in Fig. 2. Cut wire shots (CCW-32/G3) with a diameter of 0.8 mm are used in this work, and the average hardness of the measured shots is 61.1 HRC.

An A-type Almen strip is used to measure the shot peening intensity, which is 0.66 mm/A according to the SAE J443 standard [23]. The method of dye marker inks is used to verify the coverage according to SAE J2277 [15]. It is found that the nozzle moving along the root cone of the gear for one time can guarantee a coverage of 100%; thus, the coverage of 500%, 1000%, 2000%, and 4000% are shot peening for 5 times, 10 times, 20 times, and 40 times, respectively. The 5 specimens in this work are marked as SP1 (100% coverage), SP5 (500% coverage), SP10 (1000% coverage), SP20 (2000% coverage), and SP40 (4000% coverage), respectively. Several gear teeth are cut off by wire-cut electrical discharge machining (DEDM) from each specimen for subsequent characterization tests.

### 2.3 Testing methods

#### 2.3.1 Mechanical property measurements

Mechanical property measurements include residual stress and microhardness test. According to the standards of ASTM-E915-2010 [24] and EN 15305-2008 [25], the residual stress measurement is carried out by a Proto-iXRD X-ray stress analyzer. In order to get the in-depth residual stress distributions, an electropolisher (Proto, 8818-V3) is used to remove surface materials stepwise in the detection site with saturated sodium chloride solution. A VHX-5000 digital microscope is used to measure the removed depth of the surface material each time.

Hardness distribution along the depth is measured with Huayin 200HVS-5 digital Vickers hardness tester with the experimental force of 9.807 N and loading time of 10 s.

| Elements | C      | Mn     | P      | S      |
|----------|--------|--------|--------|--------|
| Content (wt.%) | 0.203 | 0.861  | 0.009  | 0.0283 |

Table 1 Chemical composition of 22CrMoH alloys
2.3.2 Surface morphology measurements

Surface morphology measurements include surface roughness test and microtopography observation. An optical profilometer (Wyko, NT9100) equipped with the Vision software is used to measure the surface roughness values and surface roughness profile at the central area of the gear tooth flank for each specimen. After 3 measurements of the most representative roughness parameters, including the arithmetic average roughness value (Ra), the total height of the profile height (Rt), root mean squared surface roughness (Rq), and the maximum height of the profile (Rz), the average value is taken as the final result for each surface roughness parameter.

For further analysis of the damages on the tooth flank, a field emission scanning electron microscope system (TESCAN, MIRA 3 LMU) is used to characterize the micro-morphology of the treated tooth flank for each specimen.

2.3.3 X-ray diffraction measurements and calculations

X-ray diffraction (XRD) diffractometer (Bruker, Advance D8) is used to qualitatively analyze the microstructure of the tooth flank treated with different shot peening coverage.

The volume fraction and crystallite size of martensite on the tooth flank are calculated using Material Analysis Using Diffraction (MAUD) software. Based on the XRD data, the Williamson-Hall (W-H) method is used to study the evolution of microstrain and dislocation density on the tooth flank \[26–28\]. The W-H equation could be expressed as:

\[
\delta \cos \theta = \frac{k D}{\lambda} + 2 \varepsilon \sin \theta \lambda
\]

Here, \(D\), \(\lambda\), \(\theta\), \(\rho\), and \(\varepsilon\) are domain size, X-ray wavelength (0.15418 nm), diffraction angle, dislocation density, and microstrain, respectively. \(k\) is Scherer’s factor, which is 0.9. \(\delta\) is the normalized full widths at half maximum (FWHM) of diffraction peaks obtained by Gaussian relations, which is given as:

\[
\delta = \sqrt{\delta_m^2 - \delta_0^2}
\]

where \(\delta_m\) is experimentally measured FWHM and \(\delta_0\) is the instrumental correction of FWHM obtained by silicon-640 standard specimen.

Williamson and Smallman \[27\] pointed out that the dislocation density \(\rho\) due to strain broadening could be expressed as:

\[
\rho = \frac{14.4 \varepsilon^2}{b^2}
\]

\(b\) is the value of the Burgers vector along the (111) direction for BCC metals.

2.3.4 Wear test

Instead of the real gears, cube-shaped steels (20 mm × 20 mm × 20 mm) of the same material, carburizing process, and shot peening parameters as the previous test gears are employed in the wear test to elucidate the wear behavior after shot peening. The tests are conducted on a ball-on-disk wear tester (CFT-I) at room temperature in dry conditions. The test steels are fixed on the rotating disk and slide against 100Cr6 steel balls (diameter of 6 mm) in a circular path of 4 mm in radius. The normal applied load is 100 N, the rotating speed is kept at 200 r/min, and the test duration is set as 90 min for each steel. Wear morphology is characterized using a SEM to determine the main wear mechanism of each test sample. The wear volume could be calculated by the equation below:

\[V = 2\pi A r\]

where \(A\) is the cross-sectional area of the wear track, which is measured using a microscope (VHX-5000 3D) and \(r\) is the wear track radius.

3 Results and discussions

3.1 Mechanical property

3.1.1 Residual stress

The influence of shot peening coverage on residual stress distribution on tooth flank is shown in Fig. 3. Because of plastic deformation and Hertz contact
pressure [29], shot peening increases the magnitude of compressive residual stress on the external surface of the gear, and maximum compressive residual stress locates on the subsurface. Subsequently, with the increase of layer depth, the magnitude of compressive residual stress decreases and gradually tends to be stable. It is concluded that increasing coverage level may not always result in a high magnitude of compressive residual stress on the external tooth surface. Similar results were reported by refs. [10, 30]. As shown in Fig. 3, the residual stress on the external surface of all peened specimens ranges from \(-518.53\) to \(-634.71\) MPa, and the value of SP1 is the highest. The reason may lie in surface damages caused by high shot peening coverage levels [31]. These results may suggest that if we intend to obtain a high compressive residual stress distribution on tooth flanks by increasing shot peening coverage, it should be considered the surface state of gears.

The measured maximum compressive residual stress is located at the depth of 50~75 \(\mu\)m and fluctuates from \(-852.63\) to \(-1172.10\) MPa. The maximum compressive residual stress is helpful to restrain the crack propagation and improve the fatigue resistance of the gear. The maximum compressive residual stress for coverage levels less than 1000% exhibits obvious growth tendency with coverage. Beyond the coverage of 1000%, there are no significant variations in the magnitude of maximum compressive residual stress, indicating that compressive residual stress has a saturation value [32]. AGMA [14] reported that the maximum compressive residual stress was about 50~60% of the ultimate tensile strength (UTS) of the peened gear surface. Accordingly, the maximum compressive residual stress of gears produced by shot peening cannot increase indefinitely.

### 3.1.2 Microhardness

In general, the microhardness value of the material after shot peening is used to characterize the cold hardening characteristics of the material. Figure 4 exhibits the microhardness variation versus coverage. Each data point represents the mean value of 3 different indentations at the same depth. It can be concluded that the variation trend of the surface microhardness of the peened gear is basically the same. Due to Hertz pressure, the hardness peak occurs in the near-surface layer, and the microhardness decreases gradually with layer depth. This is due to the reduction of grain refinement, martensite phase transition, dislocation density, and plastic deformation induced by shot peening along the in-depth direction. The higher hardness gives rise to better contact fatigue and wear resistance of the gear. If the hardness gradient changes too quickly, it will tend to form stress concentration points on the gear [33]. It is observed that the decline value of hardness in the depth of adjacent layers does not exceed 30 HV1.0 and this smooth hardness transition can exert a beneficial effect on contact fatigue and wear behavior. As shown in Fig. 4, with the increase of coverage, microhardness values at the depth of 0.1 mm in the near-surface layer increase accordingly, ranging from 656.5~747.5 HV1.0. With the increase of coverage, how much increase in hardness peak? From Fig. 4, the microhardness of SP40 at the depth of 0.1 mm increases by 13.9% compared with that of SP1. It is indicated that shot peening can promote surface work hardening effect with the increase of coverage. However, from SP1 to SP40, the hardness at the depth of 0.1 mm increases by 6.49%, 3.39%, 0.83%, and 2.57%, respectively. It is noted that the increasing trend of the hardness peak slows down. No obvious changes occur with increasing coverage, especially beyond the coverage of 1000%. This phenomenon indicates that the plastic deformation of the material has reached a limit, and the high dislocation density and carbon content prevent the further accumulation of local plastic strain near the surface [34]. Therefore, it can also be concluded that there exists a saturation value of hardness for shot-peened gears under a different coverage.

From the microscopic point of view, the improvement of surface hardness of the gear is due to the evolution of surface microstructure induced by shot peening, that is, the decrease of residual austenite caused by martensite transformation and the refinement of grains according to the classical Hall-Petch relationship [35]. The martensite transformation reflects the level of cold hardening and is proportional to the residual stress to some extent. The greater residual compressive stress on the surface layer of the material indicates more residual austenite transformation, thus leading to a high hardness. Therefore, it can be seen that the hardness peak is consistent with the peak value of compressive residual stress shown in Fig 3.
3.2 Surface morphology

3.2.1 Surface roughness

Shot peening changes the surface roughness of gears, which is considered a negative factor. Figure 5 shows the average surface roughness values in the forms of $Ra$, $Rq$, $Rt$, and $Rz$ under a different coverage. All surface roughness values are defined according to ISO 25178-2 [36]. What can be observed is that the variation trend of each surface roughness parameter is similar. It is worth noting that the surface roughness decreases with increasing coverage levels and then increases slightly. Surface roughness reaches the minimum value under the coverage of 1000% in this work. In most cases, engineers mainly focus on the surface roughness of $Ra$. From Fig. 5, the surface roughness $Ra$ of SP5 is about 21.28% less than that of SP1, whereas the reduction is about 7.15% for $Rz$. It is revealed that a proper increase of coverage can reduce the surface roughness of gear tooth flanks, and the results are compatible with that of other literature [10, 17, 32, 37].

3.2.2 Microtopography

Figure 6 presents the surface roughness profiles and SEM observations taken from the peened gear tooth flanks. Figure 6a shows some hobbing marks like knife scars are clearly visible on the surface of SP1, and the texture has directionality. With the increase of coverage, the hobbing marks gradually disappear, surface directionality is diminished, and the plastic deformation introduced by shot peening is increased (Fig. 6b–e). The impacts of shots and some surface cavities can be seen on all treated specimens. Figure 6a–c shows very few microscalings on the peened gear surface [10, 38]. More notably, beyond the coverage of 1000%, the population of tooth surface microscalings goes up, the surface layers begin to peel off, and the spallings occur on the peened gear surface as shown in Fig. 6d. As depicted in Fig. 6e, the surface is severely damaged and considerable microscalings, spallings, and burrs are formed. Such damages created by the overlapping of peening dimples and surface plastic deformation can often be found around the hobbing marks or between the dimple boundaries, which could cause premature crack initiation on tooth flanks. Some researchers also got similar SEM characterization observations on other materials [10, 39–44]. To conclude, it is inevitable that defects generate on the peened surface of gears as clearly seen in the SEM images. Different shot peening parameters may result in different damages on the surface, so shot peening parameters should be adapted to the gear material and geometry.

The surface microtopographies have good consistency with the surface roughness data presented in Fig. 5. The higher roughness values for SP1 lie in the deep craters and hobbing marks, which increase the height of the peak on the surface. Due to enhanced cold work hardening of the gear by continuous shot peening bombardment, the craters are flattened and hobbing marks are undermined, thereby inducing a smoother surface for SP5 and SP10. Compared with SP5, the smaller roughness values for SP10 are related to the shallower craters and hobbing marks on the surface. The reason why surface roughness values for SP20 and SP40 are larger is that numerous damages and considerable plastic deformation appear on the surface. It is suggested that shot peening above the coverage of 1000% is not recommended because of overpeening [45].

3.3 XRD analysis

3.3.1 Phase transformation

Figure 7 shows the XRD patterns of the topmost surface of the gears peened with different coverage levels. The number of diffraction peaks does not change, which indicates that the gear treated with different shot peening coverage cannot generate a new phase. The phase is dominated by martensite (M), which is caused by the transformation from austenite to martensite induced by plastic strain after shot peening. The results are consistent with the findings expressed by other refs. [46–50]. Based on the Rietveld whole pattern fitting method, the volume fraction of martensite can be evaluated to be about 84.38%, 85.27%, 87.26%, 91.53%, and 95.81% corresponding to SP1, SP5, SP10, SP20, and SP40, respectively. Therefore, increasing shot peening coverage can improve the phase transformation from austenite to martensite.
(a) SP1 (100% coverage)

(b) SP5 (500% coverage)

(c) SP10 (1000% coverage)

Fig. 6  a–e Surface roughness profiles (left) and SEM images (right)
3.3.2 Crystallite size

The crystallite size on the tooth flank can be calculated to be about 36.88 nm for SP1, 36.43 nm for SP5, 34.24 nm for SP10, 31.25 nm for SP20, and 28.79 nm for SP40 respectively. Figure 8 shows a typical Rietveld plot of SP40 on the tooth flank and the Sig value is about 1.16. The values of Sig are 1.33, 1.23, 1.29, and 1.27 for SP1, SP5, SP10, and SP20, respectively. The Sig values which represent the refinement error are close to 1, indicating that the refinements are reliable [51].

In addition, as depicted in Fig. 7, the FWHM value at the topmost surface for (110) lattice plane increases with coverage levels, and the value of SP40 increases by 32.16% compared with that of SP1. This is due to the generation of plastic deformation on the gear surface layer induced by continuous impacts of shot streams, which leads to grain refinement and lattice distortion [52]. From XRD data, it is noted that crystallite size is negatively correlated with FWHM [53].

3.3.3 Microstrain and dislocation density

According to Eq. (1) and Eq. (2), the relation scatter diagram between $\delta \cos \theta / \lambda$ and $2 \sin \theta / \lambda$ for different diffraction peaks is shown in Fig. 9. The slope which represents strain $\varepsilon$ is obtained by linear fitting, and dislocation density can be calculated using Eq. (3). Figure 10 shows the variations of microstrain and dislocation density with coverage on the tooth flanks. It is revealed from the results that microstrain and dislocation density increase slowly with shot peening coverage levels. The microstrain ranges from 0.008 to 0.0126, whereas the dislocation density ranges from $1.52 \times 10^{16} \text{ m}^{-2}$.
Dislocation density is related to microstrain, so it is shown that the calculated dislocation density has the same trend as the microstrain on the gear tooth flanks. Shot peening induces cyclic plastic deformation on the gear tooth flank, and the process of plastic deformation is in fact the result of dislocation movement on the surface layer. Greater deformation resistance results in a stronger ability to hinder the dislocation movement. Compressive residual stress induced by the shot peening offsets the external load, which indicates that shot peening reduces the driving force for the dislocation movement and hinders the crystal slip on the surface layer. The dislocation density increases due to the increase of plastic strain after shot peening; with the increase of coverage, dislocation tangle, interaction, and pile-up take place in the material and then evolve into subgrain boundaries in this process; the grains are refined finally [54, 55]. This phenomenon is becoming more and more serious as coverage increases. It is logical that grain refinement represents the increase of grain boundary, which provides better resistance to the dislocation movement for the material. Consequently, the hardness of the material can be enhanced at the macroscopic level.

3.4 Wear behavior

Figure 11 illustrates the worn surface morphologies of the treated gear steels. From 100 to 1000% coverage, the worn surfaces of the gear steels show obvious plowings, and the number of spallings and adhesives decreases. It can be concluded that the wear mechanism has the tendency of changing from adhesive wear to abrasive wear with the increase of shot peening coverage. However, when the coverage levels are too high (from 2000 to 4000%), the worn surfaces become more and more serious and the wear mechanism changes from abrasive wear to adhesive wear. According to Eq. (4), the wear volumes of the test steels are shown in Fig. 12. The comparative analysis demonstrates that shot peening with the coverage of 1000% can lead to a better wear resistance.

The wear behavior of gears depends on the surface integrity. Specifically, the enhancement of compressive residual stress...
stress by increasing shot peening coverage can delay the initiation and propagation of cracks during wear. Grain size refinement can increase the threshold of crack initiation [55]. The enhancement of hardness related to grain refinement and martensite transformation can make the gears withstand higher loads [56, 57]. However, increasing shot peening coverage results in a variation of surface roughness and surface topography. When the surface roughness and topography are severely deteriorated and greatly counteract the positive effects of compressive stresses, grain refinement, martensite transformation, and so on, the wear resistance of gears could not be effectively improved.

4 Conclusions

(1) With the increase of shot peening coverage from 100 to 4000%, the top surface residual stress is in the range of $-518.53$ to $-634.71$ MPa, whereas the maximum residual stress varies from $-852.63$ to $-1120$ MPa. The maximum compressive residual stress for coverage levels less than 1000% exhibits obvious growth tendency with coverage. However, there are no significant variations in the magnitude of maximum compressive residual stress beyond the coverage of 1000%. There exists a saturation value for maximum residual compressive stress.

(2) Shot peening can enhance the surface hardness from 656.5 to 747.5 HV1.0. Near-surface hardness on the tooth flank is positively correlated with coverage levels, but it
has a saturation value. Beyond the coverage of 1000%, the increasing trend of the hardness peak slows down.

(3) The roughness value on the gear tooth flank can be reduced if the coverage is appropriately increased. Beyond the coverage of 1000%, numerous damages are easily created on the gear surface in the form of microscalings, spallings, burrs, etc., which cause crack initiation.

(4) With the increase of shot peening coverage from 100 to 4000%, the volume fraction of martensite can be increased from 84.38 to 95.81%, and the crystallite size can be refined from 36.88 to 28.79 nm. The dislocation density is in the order of $10^{16} \text{m}^{-2}$ and the microstrain ranges from 0.0085 to 0.0126.

(5) Taking into consideration of surface integrity and wear test results, the coverage of 1000% is the optimal coverage for heavy-duty-axle gears in shot peening.

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Declarations

Ethics approval Not applicable.

Consent to participate We confirm.

Consent for publication We confirm.

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