Simulation analysis of shot peening on the surface of high-load connecting rod

Long Bai¹, Jianjun Chen¹, Guoxiang Liang¹,³, Tian Tian¹, Lijing Xie² and Quanping Li¹
¹ Shanxi Diesel Engine Industry Co., Ltd, Datong Shanxi, 037036, China
² Beijing Institute of Technology, Beijing, 100081, China
³ Email: 442918783@qq.com

Abstract. This paper is aimed at the high load connecting rod of the engine, which bears huge combustion pressure and inertia during the working process. Using process simulation technology to establish limited shot blastMeta-model, the law of influence of shot peening time, shot speed, shot angle, shot diameter and other parameters on the surface integrity of the connecting rod was obtained. The shot peening test of the connecting rod verified the correctness of the simulation and reached the project technical requirements.

1. Introduction
The connecting rod is a key moving part of the diesel engine, it not only bears the high burst pressure of fuel from the combustion chamber, but also the high-speed moment of inertia during the working process. The connecting rod material studied in this paper is 34CrNiMo6, which is a typical difficult-to-machine material with poor processability[1-2]. The connecting rod is a typical moving part of a complex alternating load-bearing structure, which has strict requirements on the fatigue resistance of components. In order to significantly improve the fatigue resistance of parts, Strengthening the connecting rod shaft by shot peening [3-5].

Shot peening is the impact of high-speed steel shots on the surface of the part, causing the metal surface to crack, crystal lattice distortion and high-density dislocations. After the long and enough shot blasting, the metal surface material will occur plastic flow, which causes plastic deformation of overlapping pits. In the process of forming the pits, compressive stress is induced and the surface structure is stretched, and residual compressive stress is formed on the surface and the subsurface layer, thereby the physical and chemical properties of the material is significantly improved [6-10].

In this paper, based on the principle of shot peening, a 34CrNiMo6 connecting rod shot peening strengthening finite element simulation model is established [11-13]. Through simulation calculation, the effect of shot peening process parameters on the surface residual stress and coverage is analyzed. The simulation results are verified by shot peening tests and optimize the shot peening process parameters of the connecting rod.

2. Construction and post-processing of shot blasting finite element model
2.1. Determine Rayleigh damping and volume viscosity
The mises stress of the element at the center of the impact during the incident of a single projectile is used as the judgment index. The influence of the volume viscosity and Rayleigh damping on the
stability of the calculation results was investigated according to the index. It can be seen from Figure 1 and Table 1 that in the absence of Rayleigh damping, simply increasing the volume viscosity will improve the calculation stability, but still cannot reach stability. The use of Rayleigh damping can make the calculation results quickly and stably, and the accuracy of the calculation results can be guaranteed. The Rayleigh damping and increased volume viscosity increase the calculation time, and at the same time, the stability value deviates from the correct value. Therefore, this paper uses Rayleigh damping alone as the artificial viscosity to stabilize the calculation results.

Table 1. Effect of different artificial viscosity on the stability of results and calculation time.

| Category                                         | Impact time(s) | Total calculation time(s) | Steady increment(s) | stable schedule(s) |
|--------------------------------------------------|----------------|---------------------------|---------------------|-------------------|
| No Rayleigh damping, default volume viscosity    | 5e-5           | 1324.3                    | 4.66e-09            | Not stable        |
| Rayleigh damping, default volume viscosity       | 5e-5           | 1339                      | 4.67e-09            | 3.88e-5           |
| Volume viscosity = 0.6, without Rayleigh damping | 5e-5           | 2269                      | 2.73e-09            | Not stable        |
| Volume viscosity = 0.6, Rayleigh damping         | 5e-5           | 2274                      | 2.72e-09            | 3.3e-5            |

Figure 1. Effect of different artificial viscosity on the stability of the calculated results.

2.2. Projectile modeling
An analytical rigid body projectile model was established. Because the hardness of the projectile is greater than the hardness of the target, the amount of deformation of the projectile in the projectile-target contact can be ignored. The analytical rigid body model can only be taken as a shell, and it does not have physical quantities such as solid mass and moment of inertia. These physical quantities need to be assigned to the reference points of the analytical rigid body separately. The established model was shown in Figure 2, and the reference point was set at the center of the sphere.
The process of generating the random projectile ball center position was shown in Figure 3. Figure 4 showed a shot blasting model with an angle of incidence $\phi = 70^\circ$, the number of projectiles $N = 1004$, and the diameter of the projectile $D = 1.2$ mm. The positions of all projectiles in space satisfied a uniform random distribution.

The velocity of the projectile is given by the initial velocity field, and its direction is guaranteed by the velocity components in x and z directions. The initial velocity application point is the reference point for all rigid body projectiles.

The general contact is used to define the contact between each projectile and the target surface, and set the friction coefficient $f = 0.3$.

### 3. Simulation research on surface integrity of shot peening parts

#### 3.1 Effect of shot peening time on surface residual stress

The variation law of shot peening residual stress with time is shown in Figure 5. It can be seen from the figure that the surface residual stress first increases with the shot peening time and then fluctuates in a small range near a certain value. Due to the hardening characteristics of the material, the magnitude of the residual stress decreases with increasing shot peening time, until the stress state of the target surface reaches stability, and the locally incident projectile will slightly change the local distribution of the surface stress, but the impact on the entire surface is very limited. Both the value and depth of the maximum residual compressive stress increase with the shot peening time and gradually stabilize, and the depth of the residual compressive stress layer also has a similar change law.
3.2. Effect of shot peening speed on surface residual stress

The fluctuation range of projectile speed is limited by the projectile diameter and the required shot blasting Almen intensity. When the Almen intensity is kept constant, the diameter of the projectile increases and the velocity of the projectile decreases accordingly. On the contrary, the diameter of the projectile decreases and the velocity of the projectile increases. For smaller diameter projectiles, the speed usually needs to reach 80m/s ~ 200m/s, while for larger diameter projectiles (d ≥ 5mm, mostly used for ultrasonic vibration shot peening), the velocity is often lower than 15m/s. In this article, according to the actual projectile diameter (1.2mm), the projectile velocity was set to 20m/s, 30m/s, 40m/s, 50m/s, 60m/s, and other parameters were set as follows: the number of projectiles N = 150, the incident angle φ = 90°, the projectile diameter is 1.2mm. When analyzing the effect of shot blasting speed on other surface integrity parameters, the same set of parameters was still used.

It can be seen from Figure 6 that the surface residual stress does not change significantly with the speed. The maximum residual compressive stress slowly increases with the increase of the speed. The depth at which the maximum compressive stress is located and the depth of the residual compressive stress layer both increase with increasing speed. From the perspective of energy, the greater the speed, the greater the energy transferred from the projectile to the target during impact, the greater the plastic deformation of the crater, the greater the residual stress value inside the target and the deeper the depth. The situation of the surface layer is relatively complicated. As can be seen in Figure 7, in the shallower surface layer (area A), the collision of the projectiles reduces the surface strain, so when the projectile speed increases, the mutual interference between the projectiles also increases, and the stress on the surface (and the superficial layer) will not change much.

3.3. Effect of projectile diameter on surface residual stress

The steel shot used for shot peening has certain specifications. The specifications are mainly distinguished according to the diameter of the shot. The common shot specifications and the diameters corresponding to each specification are shown in Table 2.
Figure 6. Effect of shot blasting speed on surface residual stress.

Figure 7. Interference diagram of projectile interference.

Table 2. Specifications and diameters of commonly used projectiles.

| Specification | Diameter (mm) |
|---------------|---------------|
| S230          | 0.6           |
| S330          | 0.85          |
| S390          | 1.2           |
| S550          | 1.4           |

Figure 8 shows the effect of the projectile diameter on the residual stress field produced by shot peening. The impact of different projectile diameters on the surface residual stress of the part is not significant. As the projectile diameter increases, the maximum residual compressive stress increases first and then decreases. Both the depth of the maximum residual compressive stress and the thickness
of the residual compressive stress layer increase with the increase of the projectile diameter. Both are approximately linearly related to projectile diameter.

3.4. Effect of shot peening speed on coverage
The shot blasting speed determines the size of the crater area. A larger shot blasting speed means a larger crater area, which means that a higher shot blasting speed can reach the specified coverage rate faster and improve production efficiency. Figure 9 shows that the coverage values corresponding to different speeds when the projectile radius is 0.6mm, the incident angle is 90°, the shot area is 9.3636mm², and the shot time is 0.001732s.

![Figure 9](image.png)

**Figure 9.** Variation of coverage with shot peening speed.

3.5. Effect of shot peening angle on coverage
The impact of the shot peening angle on the coverage can still be analyzed in conjunction with the movement of the shot relative to the target surface. When the incident angle is small, the velocity component of the projectile perpendicular to the target surface is small, and the crater area is also small, so the coverage is also small. As the incident angle increases, the crater area gradually increases, and the coverage rate also increases. Figure 10 shows that the relationship between different incident angles and shot coverage when the shot radius is 0.6mm, the shot velocity is 40m/s, the shot area is 9.3636mm², and the shot time is 0.001732s.

3.6. Effect of projectile diameter on coverage
When the number of projectiles is kept constant, as the diameter of the projectile increases, the area of a single projectile also increases. Therefore, according to the Aflamy equation, the shot coverage increases. As the projectile radius increases, the increase of the rate of coverage first increases and then decreases. This is also consistent with the derivative result of Figure 11.

4. Experimental verification study

4.1. Experimental study of shot peening surface integrity and finite element verification
The cast steel shot was used as the shot in the test, which with a model number of ES390P, a shot diameter of 1.2 mm, and a hardness of about 55 HRC. The test connecting rod material is 34CrNiMo6 and the surface hardness is 35HRC.

The stress detection device is an iXRD type X-ray stress tester as shown in Figure 12.
Adjusted the linear velocity of the shot blasting machine to 20m/s, 30m/s, and 40m/s respectively. Each sample was shot peened at each speed, and the shot peening time was 1 minute. After the shot peening, the specimen shown in Figure 13 was removed for stress measurement. The measurement method is X-ray diffraction (XRD). For the residual stress inside the sample, the surface layer was removed by electrolytic polishing, and the internal material was exposed to the outside before measurement. The electrolytic solution was a saturated NaCl. The thickness of the material removed
during each polishing was about 50μm. The thickness was measured by a digital micrometer. Figure 14 shows the results of the residual stresses obtained from the tests.

![Residual stress curve of shot peening at different speeds.](image)

**Figure 14.** Residual stress curve of shot peening at different speeds.

It can be seen from Figure 14 that as the projectile speed increases, the depth of the shot compressive residual compressive stress layer increases significantly, the surface residual compressive stress also increases to a certain extent, and the maximum residual compressive stress does not change significantly, but its depth has increased significantly.

4.2. Experimental study on dislocation density

PHLIPSAPD-10 X-ray diffractometer was used, and set the following parameters: Co target, tube current 30mA, tube pressure 30kV, graphite crystal monochromatic body, scanning step size 0.02°, scanning range 45°~115°, integration time 0.4 seconds. The sample was subjected to shot peening at a speed of 30m/s for one minute. The dislocation densities of the surface of the sample and the distance from the surface 200μm, 500μm (matrix material not affected by shot peening) were measured.

The obtained diffraction pattern and dislocation density can be seen from Figure 15 that the dislocation density on the shot peening surface (Figure a) is one order of magnitude higher than that of the material matrix (Figure c). Therefore, shot peening significantly increases the dislocation density on the surface of the part. The high dislocation density prevents cracks from being affected by staggered dislocations during propagation, which reduces the propagation speed and increases the fatigue life of components.

4.3. Study on surface strengthening technology of connecting rod

Shot peening medium, shot peening flow rate, shot peening time, and shot angle are the main factors that affect the morphology and residual stress of the shot peening surface. When the shot peening medium is determined, the shot peening flow and shot time directly affect the shot peening topography and residual stress. Based on the main factors, five shot peening flow and shot peening time test schemes using the arc height value, surface residual stress and surface morphology of Alman test pieces as criteria were designed. The test equipment is the existing linkage production line shot blasting machine (model: Q3518). The shot blasting medium is a cast steel shot with a diameter of 1.0mm specified by the TV5037 standard. Four Alman test pieces were used for each scheme. Surface morphology is fine and uniform after shot peening, and the fifth scheme stress value is more uniform, the surface morphology is better, so the fifth scheme is determined as the surface shot peening process plan.
Experimental research shows that shot peening can significantly increase the dislocation density, thereby increasing the number of fixed dislocations, increasing the entanglement between dislocations, inhibiting further movement of dislocations, and effectively inhibiting the initiation of cracks. It is because cracks are caused by dislocation motion.

After the surface hardening of the physical sample of the connecting rod through the fifth scheme, the technical indicators obtained are shown in Table 3:

| factor                                      | technical indicator          | achieved accuracy index     |
|---------------------------------------------|------------------------------|-----------------------------|
| Arc height of Almen type A standard test piece | 0.35±0.05                    | 0.30-0.38                   |
| Residual stress on the surface of the connecting rod | -400≈-500Mpa                | -421≈-498Mpa                |

5. Conclusion

After establishing the parameters required for the simulation analysis: the projectile type is S390, its diameter is 1.2mm, and the projectile hardness is 55HRC, which can be considered as a rigid body in the simulation. According to the spatial distance relationship between the connecting rod and the impeller of the shot peening equipment, the range of incident angle of shot peening can be determined. Since this range is not particularly large, the average value of the incident angle is taken as approximately 60°. The incident velocity of the projectile can be considered as the linear velocity of the impeller edge, which is 40m/s. The shot peening time is 1 minute. This is the length of time that engineers set according to the requirements of 100% coverage. It is impossible to simulate such a long time in actual simulation. Therefore, the key parameter of 100% coverage is used to determine the simulation time. The final residual stress on the shot peening surface of the connecting rod is approximately -421~ -498Mpa, which is very close to the range of simulated surface residual compressive stress (400Mpa~500Mpa). Further improve the accuracy of shot peening simulation.

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