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The Effect of Controlled Shot Peening on the Microstructure and Fatigue Behavior of Wet Copper-Based Powder Metallurgy Friction Plates

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The effects of shot peening treatments on the microstructure and fatigue behavior of the teeth root in wet copper-based powder metallurgy friction plates were investigated and an efficient method for selecting optimal shot peening parameters for friction plates was proposed. Different experimental processes including microscopy observation, microhardness, roughness and X-ray diffraction measurements have been performed to characterize the treated surface of specimens. It is found that fatigue life of friction plates firstly increases and then decreases with the increase of Almen intensity, and the optimal fatigue life has improved over 55%. It is considered that both surface grain refinement and high residual compressive stress are the main ingredients responsible for the improved fatigue life. With further increase of Almen intensity, surface roughness of the teeth root gradually increases to a critical point, where rough peened surface may induce crack initiation due to stress concentration, and finally lead fatigue deteriorate.

Keywords: *friction plate, shot peening, fatigue life, surface roughness.*

1. Introduction

Wet copper-based powder metallurgy (WCPM) friction plates are widely applied in the clutch of automotive and heavy-duty equipment owing to their high mechanical strength, excellent friction and wear properties[1-4]. Friction plates are mainly fixed by mean of spline teeth on a central shaft in transmission, which would produce large impact loads between spline teeth for torsional vibration. With the continuous development of vehicle power systems, more and more serious torsional vibration phenomenon appear in clutch and have become the dominant reason for fatigue fracture. This is particularly relevant for gears whose damage in terms of resistance to fatigue at the teeth root. In fact, there are several factors tending to localise the fatigue crack initiation on the surface failure at the teeth root in the friction plate, including the tensile component of stress due to bending during teeth engagement, the remarkable notch effect at the teeth root and the intrinsic surface defectiveness. Hence, it is of great significance to restrict the fatigue fracture to extend the service life for their further application.

Different surface treatments have been carried out to improve the fatigue life of WCPM friction plates and to change their stress field. The case hardening followed by shot peening (SP) has huge advantages when compared with other surface treatments[5-8]. Especially, the fatigue damage happens through initiation and propagation of a critical flaw on the component outer layer, e.g. at persistent slip bands inclusions or grain boundary triple points. The delays in the crack initiation and their closure or even arrest after initiation are attributed to superficial compressive stress fields[9-13]. It is proved that shot peening, when using optimized parameters, can provide even a higher improvement of fatigue strength. However, how to determine an optimal design of peening parameters for the desired shape is the key problem. If the SP parameters are not well chosen, there is a risk of deteriorating or altering the integrity of the target surface by inducing superficial defects such as micro-cracks and surface roughness imperfections, which is usually considered as the "overpeening" and has a strong negative influence on the materials fatigue strength[14,15].

There are also numerous experimental studies attempting to measure the residual stress distribution, fatigue life and the influence of SP parameters[16-18]. The majority of the experimental studies have used specific targets, so there are a lot of difficulties when the traditional fatigue lifespan assessment method is used in evaluating the life of friction plates. Modelling the entire shot peening process and measuring the residual stress within full-scale component are both time consuming and expensive and would not allow a careful examination of the effect of the parameters on the residual stress pattern. Finite element method (FEM) provides a powerful method for establishing quantitative relationships between shot and

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target parameters and residual stress characteristics[19-22]. But SP treatment is a very complex process that depends on many variables such as the shot diameter, the shot velocity, the coverage ratio, the shooting angle, the material of shots and sheets. The FEM results show significant differences when compared with those experimental measurements. Therefore, for a long time, the shot peen forming is a trial-and-error process. The experience of operators still play a very important role in the process.

In this paper, a specialized fatigue life estimation system is designed for the WCPM friction plates. The effects of shot peening with four different parameters on the fatigue behavior of friction plates are investigated. A quick and efficient optimization method is developed to choose best technology parameter for shot peening. The surface residual stresses, hardness, microstructure, surface roughness and fracture morphology are evaluated to check the accuracy and reliability of the results based on the fatigue life. Our studies may exert a great impact on the synthesis of shot peening on the teeth root of friction plates and eventually on their applications in improving their fatigue life.

2. Materials and Experimental Procedures

WCPM friction plate with internal spline teeth is made by a substrate steel plate, coated with the friction materials. The number of internal spline teeth in friction plates is 122, which meets the requirements for fatigue test. The modulus of the friction plate is 3 mm. The substrate steel plate is made by 30CrMnSiA low carbon steel. The mechanical properties of the steel plate are shown in Table 1. Table 2 shows the selective parameters for SP treatments in detail, which are marked as SP1, SP2, SP3 and SP4. No shot peening (NP) specimens are induced for comparison.

Table 1. The properties of 30CrMnSiA steel

Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
200	364	740	18.5

Table 2. The different parameters for SP treatment

Label	Shot type and diameter (mm)	Almen intensity (A)	Coverage (%)
NP	—	—	—
SP1	Ceramic, Ø0.15	0.1	100
SP2	Ceramic, Ø0.15	0.15	100
SP3	Ceramic, Ø0.15	0.2	100
SP4	Steel, Ø0.3	0.3	100

In order to reduce the effects of uncontrolled factors in the present research and keep enough test sample amount, three SP treatments as a group were carried out on the spline teeth of one friction plate. The spline teeth of friction plates were divided into several sub-regions at intervals of 4 teeth. That is to say, one friction plate was treated with NP, SP1 and SP2, and the other was treated with NP, SP3 and SP4. Before one shot peening parameter processed, other spline teeth would have be covered and protected by adhesive tape. Typical shot peening treated spline teeth surface on plates is shown in Fig.1. To study the microstructure as well as the residual stresses on the surface, XRD analysis was performed using the Philips PW1050 and AST X-Stress 3000 X-ray diffractometers, respectively. The roughness of the test friction plates was measured by Olympus optical profiler using the arithmetic average roughness *R*a. The measured interference peaks were evaluated according to the sin2ψ method and angle of ψ was varied every 10 in the range from -45 to +45. Microhardness along the depth of the cross-section of teeth was measured by a Vickers hardness tester.

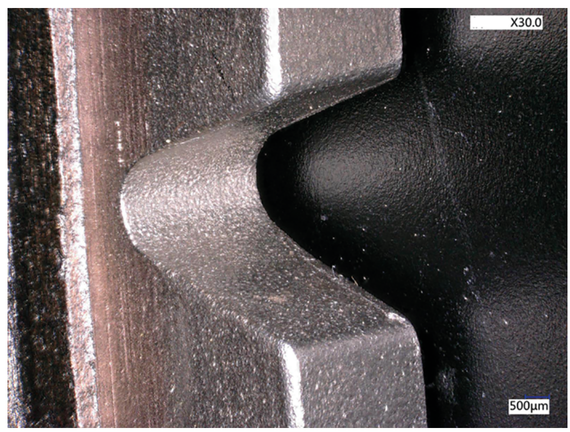


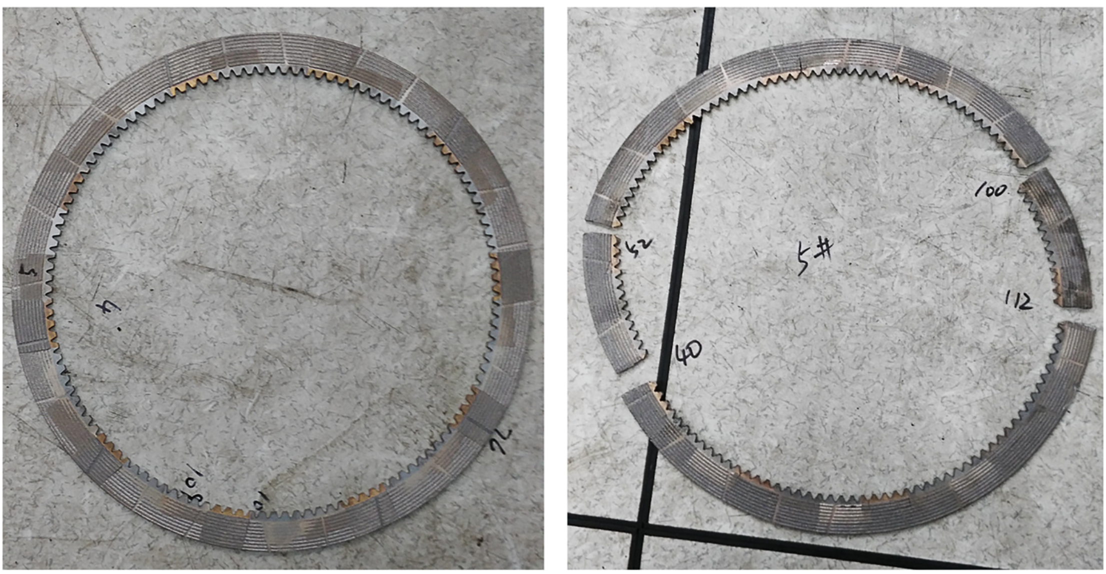
Figure 1. Typical shot peened surface of spline teeth on friction plate.

The fatigue tests were carried out by using a specialized fatigue life estimation system[23], namely dynamic strength of friction plate machine, in which the 12V150L diesel engine is the torsional vibration excitation source. During rotation process, the internal spline teeth of friction plate would engage the external spline teeth of the hub for torsional vibration. The rotational speed is about 1600rpm, while the vibration frequency is 160 Hz. Then, the fracture surfaces of the fatigue specimens were observed using the scanning electron microscopy (SEM-EDS, JEM-2100F).

3. Results and Discussion

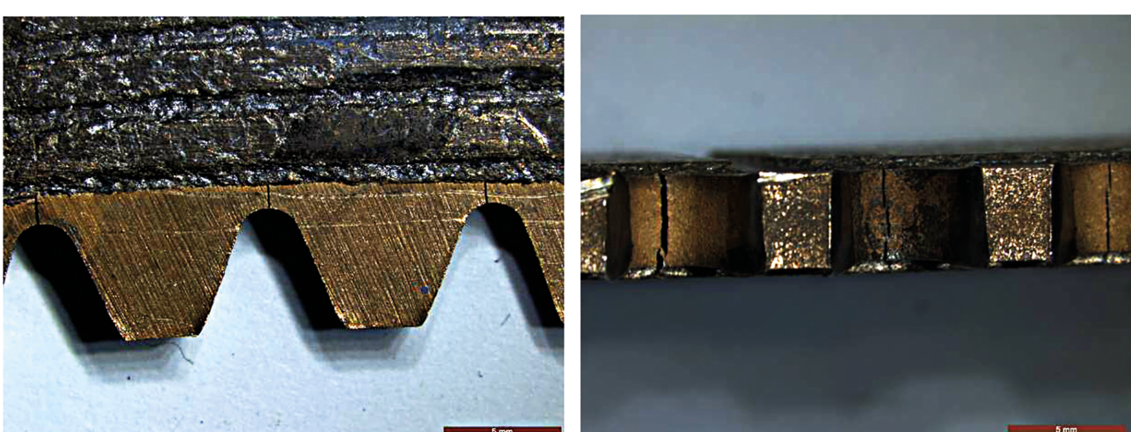
The macroscopic feature of friction plate before and after SP treatment is shown in Fig. 2. It is noted that the friction plates are broken into some pieces after fatigue tests. It can be seen that all fractures appear on NP teeth, while the SP teeth have no fracture, which demonstrates that SP treatment can improve the fatigue life of friction plates. Meanwhile, all spline teeth surfaces are thoroughly analyzed with the optical microscope. As shown in Fig. 3, some small micro-cracks are visible in the teeth root, which would result in the fracture in this site. During the fatigue test, a crack typically appears in the middle teeth root region of the specimen, indicating that the crack propagates along the direction of the teeth width. Once the crack extends beyond the thickness of the specimen, an undesired instantaneous fracture occurs. The number of cracks with different SP treatments is listed in Table 3. Main crack can be confirmed in the NP teeth by examining the fracture surfaces, which is very important for fracture analysis. It can be seen that there are the largest number of cracks in the NP teeth. Main crack is usually the initiation site for fracture appearance. Main crack happening in NP teeth demonstrate that the SP treatment can delay the expansion of fatigue crack, effectively prolong the service life of the friction plates. According to statistics, the number of cracks in SP2 treated teeth is less than that in SP1. For another condition, it is clear that the result of SP4 is better than that of SP3. In order to further obtain the optimal SP parameter, the SP2 and SP4 treatments are chosen for the second fatigue tests.

The images of the specimens before and after the second round fatigue test are shown in Fig. 4. The number of cracks in tested specimens is listed in Table 4. It is noted that the number of cracks in SP4 treatment is larger than that in SP2 one. Main crack is only found in SP4 treated teeth. The fatigue tests show that SP2 treatment is the most effective SP parameters with the least number of cracks.



(a) (b)

Figure 2. The images of one typical friction plate (a) before and (b) after fatigue test.



(a) (b)

Figure 3. The origin of the fatigue cracks from the middle teeth root region.(a) longitudinal section; (b) cross section.

Table 3. The number of cracks in tested specimens after the first round fatigue tests

Specimens	Shot peening parameter	Teeth number	Crack number
1	SP1	40	12
	SP2	40	1
	NP	42	28 (including main crack)
2	SP1	40	16
	SP2	40	2
	NP	42	27 (including main crack)
3	SP3	40	15
	SP4	40	3
	NP	42	30 (including main crack)
4	SP3	40	17
	SP4	40	0
	NP	42	24 (including main crack)

Table 4. The number of cracks in tested specimens after the second round fatigue tests

Specimens	Shot peening parameter	Teeth number	Crack number
5	SP2	61	9
	SP4	61	36 (including main crack)
6	SP2	61	7
	SP4	61	23 (including main crack)
7	SP2	61	10
	SP4	61	21 (including main crack)

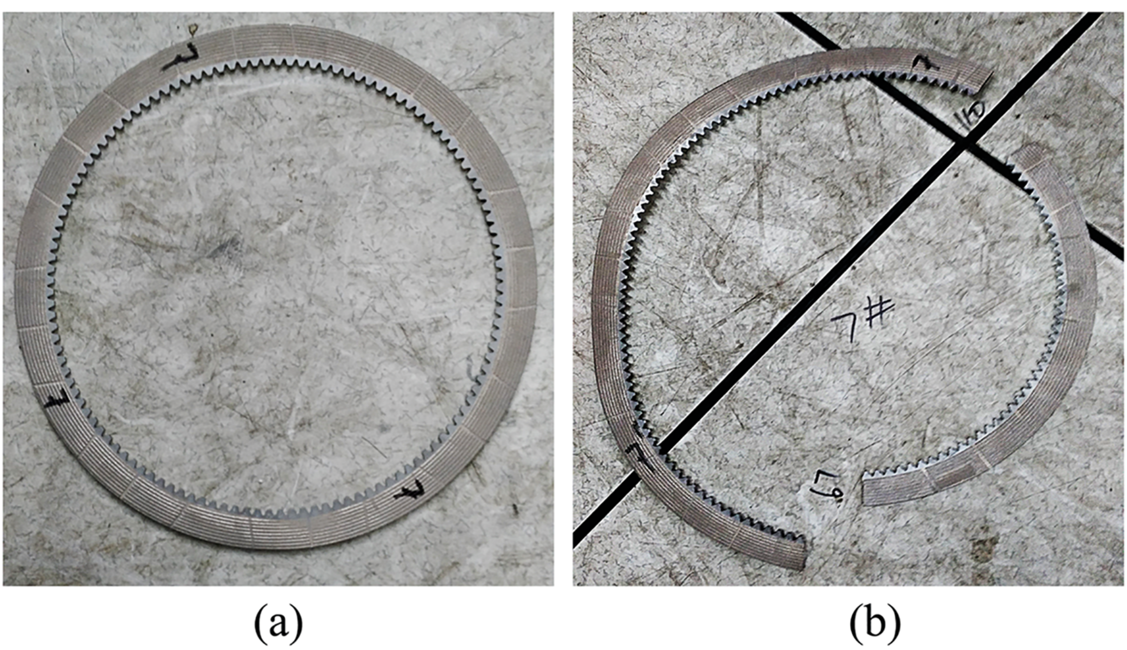


Figure 4. The specimens (a) before and (b) after the second round fatigue test.

The fatigue-fracture morphology of main crack for the above-mentioned specimen 7 is exhibited in Fig. 5. It can be divided into three regions according to the fracture patterns: the crack-initiation region, the crack-propagation region and the fast-fracture region. It is noted that the fatigue-cracks are originated from the middle teeth root, and exhibit the multiple-cracks features which initiates from the surface (Fig. 5b). We speculate that the geometry-dependent stress concentrations in the teeth root are the reason for crack initiation. Then, a crack-propagation region is observed with numerous fatigue striations as shown in Fig. 5c. An obvious arc boundary between the crack-propagation region and the fast-fracture region is also obtained. It is worth noting that the fast-fracture region with the clear vein-like patterns is located outside the arc boundary. The final overload fracture is microscopically ductile which shows the coalescence of microvoids and vein-like patterns. That is to say, at the initial stage, the crack propagates along a straight line, and exhibits the mode I crack propagation behavior.

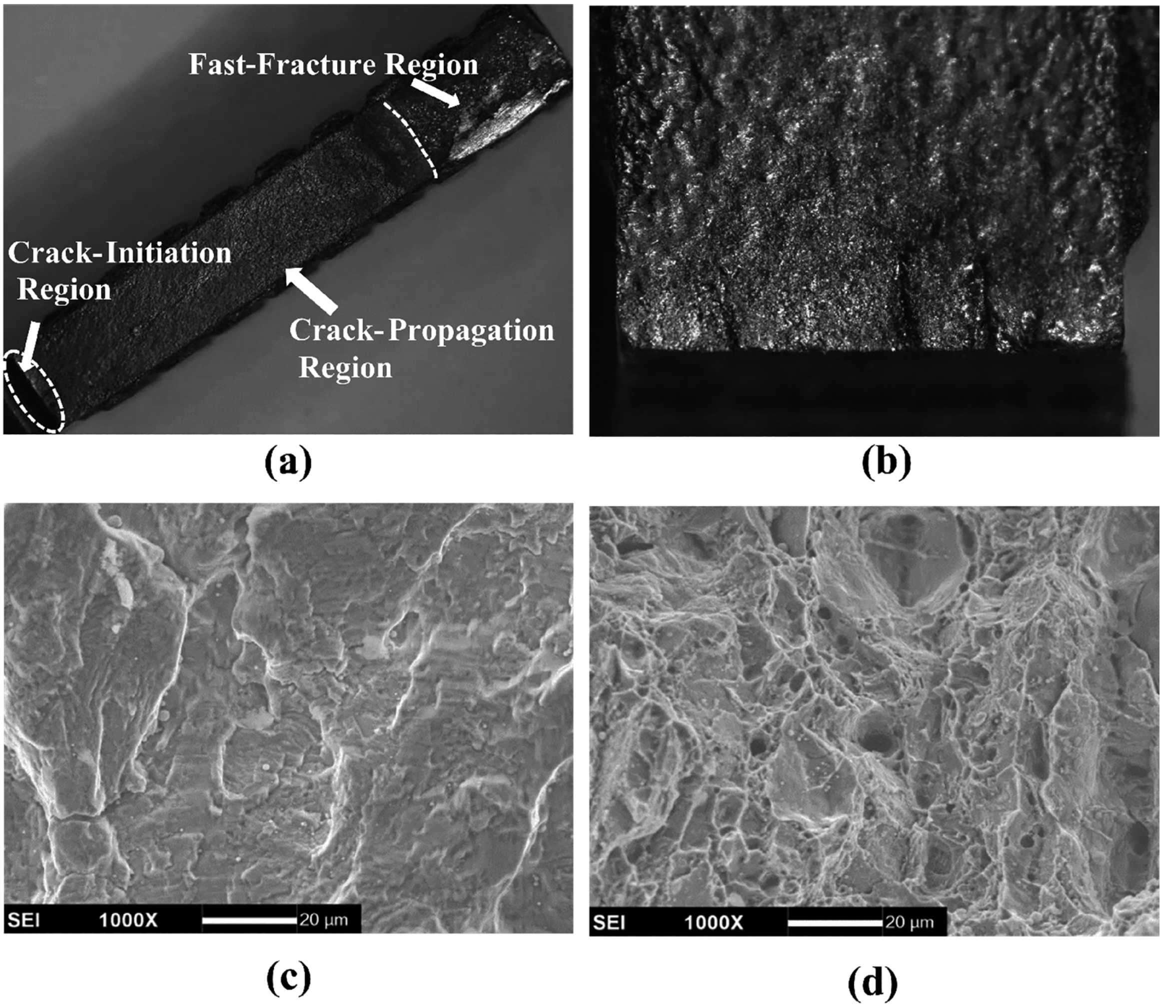


Figure 5. (a) Overall fatigue fracture surface of the specimen 2; (b) crack initiation region; (c) crack-propagation; (d) fast-fracture region.

To study the microstructure evolution as well as the surface residual stresses, XRD analysis was performed on all SP treated specimens. Both the NP and SP treated teeth exhibit the similar peaks in the XRD curves, confirming there is no obvious phase transition in the near-surface (Fig. 6a). The peak intensity of the SP treated samples exhibit a sharp drop when compared with the NP treated sample, demonstrating that the SP treatments have a strong grain refinement effects in the teeth root. Fig. 6b shows the surface residual stress of the SP treated specimens. With the increase of Almen intensity, a compressive residual stress appears in the surface of the SP treated specimens and increases sharply. The maximum residual stress is found in the SP4 specimen with the valve of -300MPa. The surface roughness of NP and SP specimens are also listed in Fig. 6b. The presented results are the average of five different measurements performed at different locations from the specimens. It notes that the average roughness for the SP treated teeth is higher than that of the NP treated ones. Specifically, the surface roughness for SP1 and SP2 teeth is about 1.6μm, which is larger than the valve of 1μm for NP treated teeth. With Almen intensity continuous increasing, the surface roughness would gradually increase to 1.8μm for SP3 treated teeth and 2.3μm for SP4 treated teeth.

A diamond Vickers indenter is also induced for measuring the microhardness along the cross section from the middle teeth root. The load was applied gradually at a constant 0.1 N/s rate with the 300g load and a dwell time of 15 s. The measurement precision is improved by averaging five testing values of at the same depth. The microhardness along the cross section from the middle teeth root is shown in Fig. 7. It is noted that the microhardness is higher on the surface and then decreases gradually going into depth. The hardening effect for SP1 treated specimen is notable till a depth of about 50 μm with the maximum of 280 HV. However, the hardening effect for SP2, SP3 and SP4 treated specimens is till a depth of about 200μm with the maximal hardness value larger than 300 HV. This microhardness variation is caused by different orientation and deformation mechanisms of grains from treated surface towards the core plate materials.

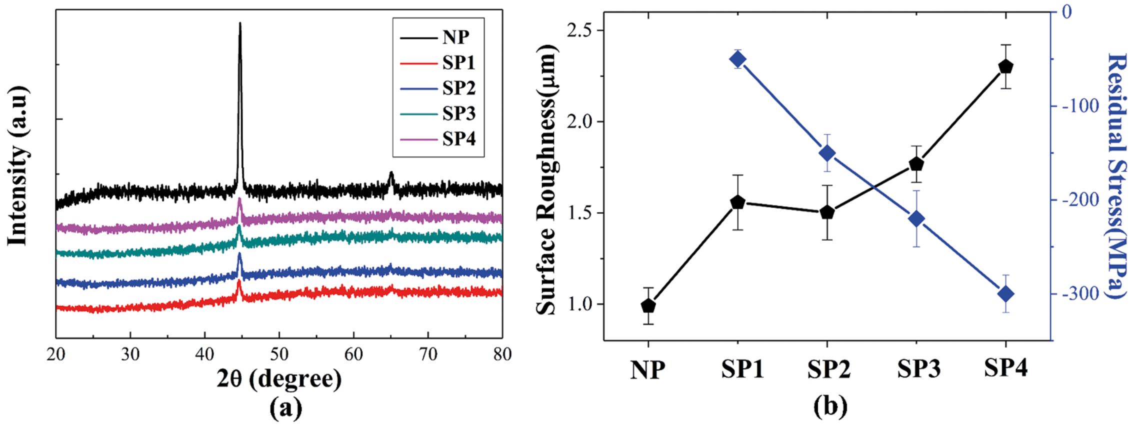


Figure 6. (a) the XRD curves and (b) the surface roughness as well as residual stress of the NP and SP treated teeth.

According to previous results, the SP2 treated specimens have the higher hardness and hardening depth, while the surface roughness is relative low, which is beneficial to prolong the fatigue life for friction plates.

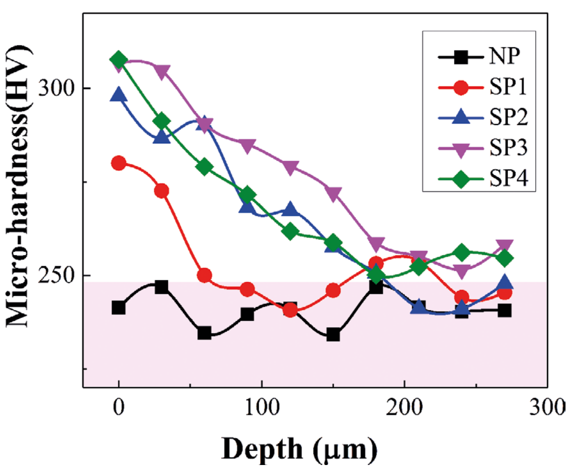


Figure 7. Microhardness variations of the NP and SP treated specimens along the cross section from the middle teeth root.

Finally, the fatigue lives for these six SP2 treated friction plates are 4.3×10^5, 4.22×10^5, 3.98×10^5, 4.1×10^5, 3.94×10^5 and 4.32×10^5 cycles respectively, which are much longer than those of the untreated ones. The most optimal SP treatment has improved the fatigue life of the friction plates over 55%.

4. Conclusion

In this work, a new method is developed to give indications on how to choose the optical shot peening parameters quickly and efficiently. Four types of shot peening SP1, SP2, SP3 and SP4 have been performed on the internal spline teeth of friction plates in order to obtain optimal result. The fatigue life of the friction plates firstly increases and then decreases with the increase of Almen intensity, in which the optimal fatigue life has improved over 55%. Careful statistical analysis of fatigue cracks on friction plate reveals the relationship between peening quality and fatigue resistance, which shows that SP2 treated teeth possess the least cracks and have the best fatigue resistance. Both the surface grain refinement and high residual compressive stress are believed to be the main ingredients responsible for the improved fatigue life. With further increase of Almen intensity, the surface roughness of the teeth root gradually reaches the critical value, where the rough peened surface may induce the acceleration of crack initiation due to stress concentration, and result in dramatically deterioration of fatigue life. This study provides an efficient way for selecting the optimal shot peening parameters of friction plates.

5. References

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