Influence of Surface Rolling Time on Short Fatigue Crack Behavior of LZ50 Axle Steel

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Abstract Based on the mean fatigue life of LZ50 axle steel specimens which were unrolled before testing, five surface rolling times were determined according to the fatigue life fraction, i.e., f=0.0, 0.3, 0.5, 0.6, and 0.7. Five groups of smooth hourglass shaped specimens which were turned and rolled at above surface rolling times were tested by a replication technique. Results show that with a given dominant short crack size, crack growth rate after surface rolling occurs much slower than that before rolling. However, the more prolonged the surface treatment is performed, the greater the growth rate occurs at the transition point between the micro-structural short crack (MSC) stage and the physical short crack (PSC) stage. Furthermore, influenced by the change of surface hardness and residual compressive stress, the effective short crack density in all the specimens, which is the average number of short cracks per unit area, decreases significantly after rolling than before. Focusing on the density after surface rolling, it is evident that the highest effective short crack density for the five studied groups of specimens increases from 662 mm^{-2} to 941 mm^{-2} with postponed rolling time. On the other hand, the average fatigue life for each group of specimens decreases with postponed surface treatment time. The average life of the initial rolled specimens was 882,562 cycles, while that of specimens turned and rolled at a 0.7 fatigue life fraction is 618,640 cycles. Therefore, the surface rolling procedure can improve the fatigue performance characteristics of the material. The choice of rolling time may affect the short fatigue crack behavior greatly. The earlier the surface treatment is performed, the better the collective effect of short cracks can be restrained as well as the longer the fatigue life of the material will be.

Keywords Fatigue, short crack, surface rolling time, LZ50 axle steel

1. Introduction

With the development of the high speed and heavy haul railway in China, the service load conditions for structures and components of railway vehicles are much poorer than before[1]. As one of the important parts for vehicle running gear, axle bears complicated alternate loadings in service, and is the component with the highest loading frequency and the most complex failure modes[2]. If the axle failure caused by fatigue damage is uncontrollable, vehicles are likely to derail, and railway operation safety will be gravely affected. For components with smooth surface under alternate loadings, short fatigue crack (SFC) initiation, coalescence and propagation normally occupy more than 70% the fatigue life[3]. For example, with a overhaul cycle of 100,000 km and a reliability of 0.999, the critical size of semi-elliptical crack on the load relieving groove of RD_2 axle is 1.23 mm, and the size of circumferential crack is only 0.94 mm[4, 5]. Thus it can be seen that the fatigue damage process of axle belongs primarily to SFC stage.

The maintenance strategy for load relieving groove of RD_2 axle, for which the final processing method is turning, is finish turning and surface rolling. However, the impact of surface treatment time choice on maintenance effect, i.e., how the surface rolling time affects the short fatigue crack behavior, is still an on-going research issue.

LZ50 axle steel is one of the widely applied axle materials in Chinese railway manufacturing industry, its production technology adopted the axle standard of AAR M-101[6]. Present research is based on the fatigue tests by a replication technique of this material. Different surface treatment times are chosen for five groups of specimens. The influence of surface rolling time on short crack propagation, crack density, and fatigue life is revealed.

2. Materials, Rolling Simulation, and Replication Tests

2.1. Test Materials and Specimens

Test material of present work is LZ50 axle steel. Its chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. The heat treatment is double normalizing and then tempering in accordance with the Chinese railway standard, TB 2945-1999. After heat treatment, the microstructure of material is coarse ferrite particles and layered pearlite particles. The banded structure is quite obvious (Figure 1a), the mean value of intervals between two rich pearlite bands, d_2, is about 109 μm with high dispersion. Gathering effects exist in both ferrite structure and pearlite structure (Figure 1b). Average equivalent diameters for ferrite grains, d_1, is 14.6 μm[7]. Totally 33 smooth axial hourglass shaped specimens with 10 mm diameter were machined (Figure 2).

Table 1. Chemical composition of LZ50 axle steel (wt. %)

C	Si	Mn	Al	Cr	Ni	Cu	P	S
0.47	0.26	0.78	0.021	0.02	0.028	0.15	<0.014	<0.01

Table 2. Mechanical properties of LZ50 axle steel

σ_b / MPa	σ_s / MPa	δ / %	Ψ / %	E / MPa
656.43	383.57	54.71	26.57	209750

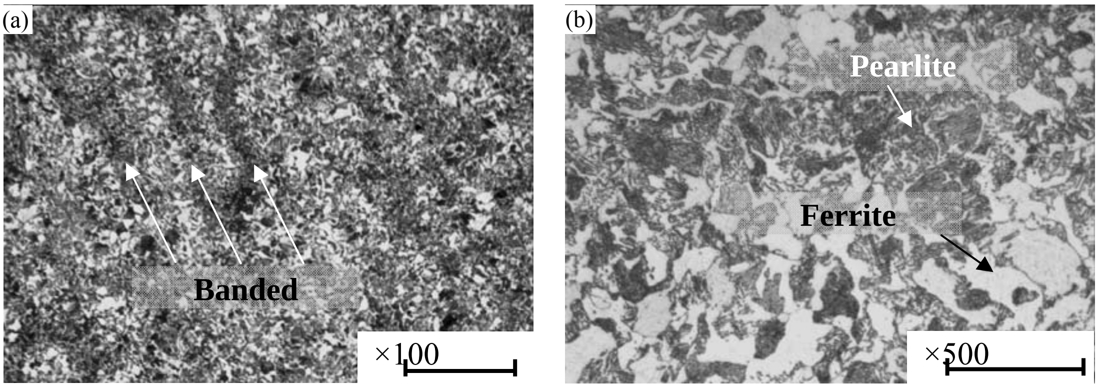

Figure1. Low (a) and high (b) magnified OM images of LZ50 axle steel after heat treatment

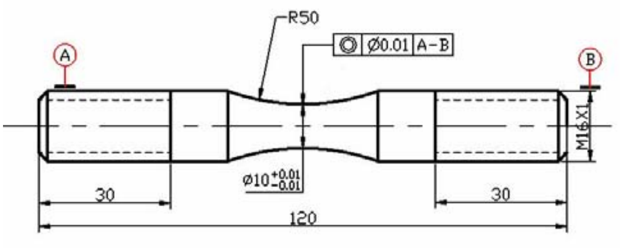

Figure 2. Schematic of shape and dimension of the specimen for fatigue test (Unit: mm)

2.2. Surface Rolling Simulation

The machining technology for load relieving groove of RD_2 axle is listed in Table 3 in detail. The purpose of finish turning is to remove possible surface cracks, while surface rolling is to strengthen the surface of load relieving groove. Surface treatment parameters of present research are also listed in Table 3. It can be seen that the simulation technology meets the maintenance requirements of real RD_2 axle. After rolling, surface Vickers hardness of specimens increases from 201.68 $HV_{0.1}$ to 222.90 $HV_{0.1}$. Meanwhile, absolute value of axial and circumferential compressive stress for specimens after surface rolling is about 170 MPa and 101 MPa higher than that before rolling[8].

Table 3. Practical repair procedure for RD2 axle and simulated surface treatment procedure for specimen

Procedure	Indicator	In practice	In simulation
Finish turning	Equipment	Numerical control machine	Numerical control machine
	Rotate speed of axle	≥350 r/min	=350r/min
	Cutting thickness	≤0.2 mm	≤0.15 mm
	Feeding speed	40~70 mm/min	=50 mm/min
Surface rolling	Equipment	Numerical control machine	Numerical control machine
	Rotate speed of axle	330~400 r/min	=350 r/min
	Rolling time	1	1
	Diameter deformation	≤0.02 mm	≤0.02 mm

2.3. Replication Tests

Replication technique is a widely applied fatigue test method in short crack research field. Test is interrupted at given time intervals (depending on the number of cycles), then replicate specimen surface with softened acetyl cellulose films, and finally these films can be dried and preserved for subsequent observation[9]. Present tests were performed under a stress-controlled sine wave mode on Rumul 250 kN high frequency fatigue test machine. The symmetrical cyclic stress amplitude was 230 MPa. To study the relationship between cracks and micro structures, specimen surfaces were etched by 4% nitric acid alcohol and the metallographic structure was exposed.

Firstly, all specimens without surface rolling were tested according to replication technique. Secondly, when cyclic loading number met predetermined cyclic number for surface treatment, test was suspended and specimens were dismounted. Thirdly, above specimens were turned and surface rolled complying with Table 3. Finally, processed specimens were mounted on test machine again and still tested at 230 MPa by replication method to final failure. Two things are important to note:

(1) Number of loading cycles according to surface rolling time.

Previous test result has shown that the average fatigue life of LZ50 axle steel specimens without surface rolling is 137705 cycles[7]. To investigate the influence of rolling time, surface treatment time for five groups of specimens was determined according to this life. That is, surface rolling was applied when life fraction, f, was 0.0, 0.3, 0.5, 0.6 and 0.7, respectively. To facilitate the presentation, specimens were indexed according to their surface rolling time, i.e., S0.0, S0.3, S0.5, S0.6, and S0.7 specimens.

(2) Test stress amplitude after surface rolling.

After turning and surface rolling, axle diameter will be slightly smaller than before, which will lead to higher local stress level even at same service loading condition. However, the purpose of present research is to investigate the influence of surface treatment time and maintenance technology on short fatigue crack behavior for LZ50 axle steel. Increase of stress amplitude caused by size decrease at changeless test load can make subsequent analysis more complex. Therefore in present study, test load was recalculated based on actual specimen diameter after surface rolling, so that replication test could be finished still at 230 MPa.

Number of effective specimens for S0.0 to S0.7 is 6, 6, 7, 7, and 7, respectively. After tests, dried replication films, which had been flattened with two glass slides, were observed using an

Auto-Montage micro-observation system by an inverted sequence method[10]. Thus, the information of short crack initiation and propagation, such as crack size, number, and angle, was obtained.

3. Results and Discussions

3.1. Comparison of Dominant Short Crack Growth Rate

Inheriting the idea of effective short fatigue crack criterion[10-12], the relation curves between dominant short crack (DSC) growth rate, da/dN, and its size, a, with five different surface rolling times are shown in Figure 3. Following conclusions can be drawn:

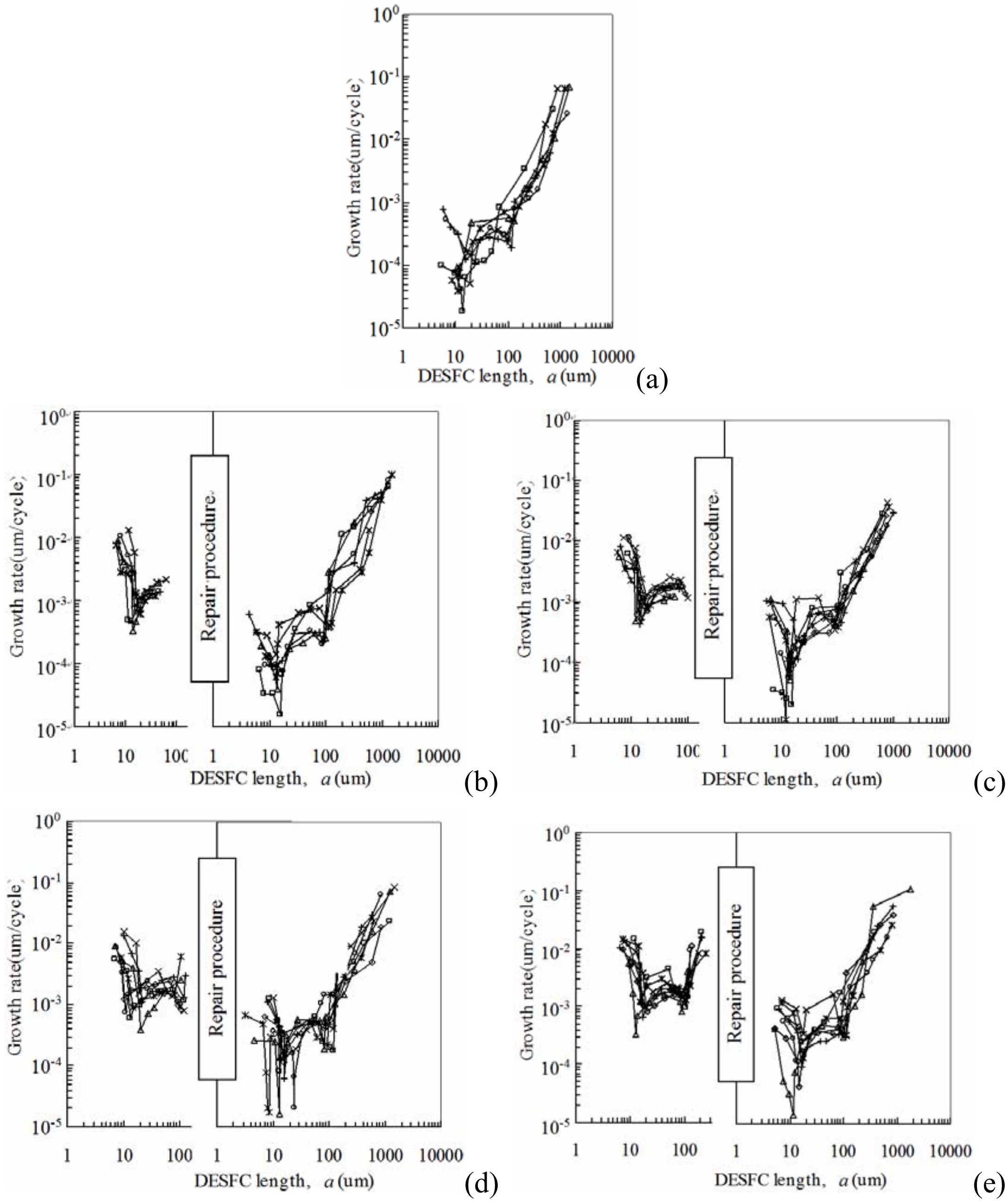

Figure 3. Dominant short crack growth rate for each group of LZ50 axle steel specimens repair times for specimens are (a) f=0.0, (b) f=0.3, (c) f=0.5, (d) f=0.6, and (e) f=0.7

(1) During crack growth process, the growth rate decelerates once or twice clearly for all these five groups of specimens. If only the crack propagation after surface rolling is taken into

consideration, it is clearly that no matter when surface treatment is performed, the crack growth rate exhibits decelerations twice in MSC stage, and corresponding DSC sizes can be seen in Table 4. At the same time, DSC sizes corresponding to growth rate decelerating time for specimens before rolling are also listed in Table 4. For S0.3 and S0.5 specimens, there are no DSC size data, because the second obvious deceleration has not appeared yet. Combined with previous study results[7], it is evident that whether or not the specimens are rolled, DSC growth rate decelerates when its size approaches ferrite grain boundary firstly and then to the pearlite banded structure. These micro-structural barriers restrain the growth of short cracks. They are inherent resistances of material, and do not change with surface rolling time.

(2) Comparing the crack growth rate curves for specimens before and after surface rolling, it is easy to judge that DSC of unrolled specimens grows much faster than specimens after rolling at the same DSC size. This may due to the difference in specimens surface condition. While surface is not rolled, its hardness and absolute value of residual compressive stress are both smaller than specimens after rolling. Fatigue performance characteristics of the material is not strengthened, thus its constraint force for crack initiation and growth is relatively weak.

Table 4. Mean value of dominant short crack size while crack growth decreases for each group of specimens

Repair time	Before repair		After repair	
	a_1, μm	a_2, μm	a_1, μm	a_2, μm
f=0.0	---	---	15.90	101.43
f=0.3	15.51	---	14.19	91.51
f=0.5	16.08	---	15.34	100.92
f=0.6	15.55	106.90	16.29	97.56
f=0.7	17.62	104.53	15.02	105.16

Note: f---fatigue life fraction according to previous test results[7], a_1, a_2---mean value of dominant short crack size while crack grow decreases for the first and the second time

3.2. Comparison of Effective Short Crack Density

LZ50 axle steel owns the character of two-stages, i.e. MSC stage and PSC stage, for the crack initiation and growth[7, 13]. Effective short crack density is the average number of short cracks per unit area in the initial zone of DSC in MSC stage. While in PSC stage, the observation regions transfer to the two zones ahead of DSC tips. The density can reflect the inherent difference of local micro-structure, and is one of the proper parameters to describe the evolutionary collective effect and statistical scatter of SFC behavior[14]. Higher density indicates the formation of micro-structural conditions for short crack growth, and also reflects the strengthen of SFC collective effect.

The changes in effective short crack density with respective fatigue life fraction for S0.0 to S0.7 specimens are shown in Figure 4. It is clear that crack density of specimens after surface rolling is much less than that of unrolled specimens. Surface treatment effectively limits the collective initiation of short cracks, and consequently weakens the promotive impact of SFC collective effect on crack propagation. However, crack density of all groups of specimens shows the same overall trend, i.e., increases in MSC stage and decreases in PSC stage. It attains the peak value at the transition point from MSC stage to PSC stage. DSC size according to density peak value is about the mean value of intervals for rich pearlite bands. It can be concluded from above discussions that the rich pearlite banded structure instead of the ferrite grain boundary is the strongest micro-structural barrier. When DSC grows to this size, SFC collective effect is further embodied. DSC is about to coalesce with other short cracks through further propagation, and enters PSC stage.

Moreover, the maximum density value for each group of specimens increases with the delay of surface rolling time. For S0.0 specimens, the mean value of maximum density is 662 mm^{-2}, while for S0.7 specimens, surface rolling time, *f*, is postponed to 0.7, and the density increases to 941 mm^{-2}. So postponed rolling time will lead to strengthened SFC collective effect, so that local micro-structure conditions get more and more advantageous to DSC growth.

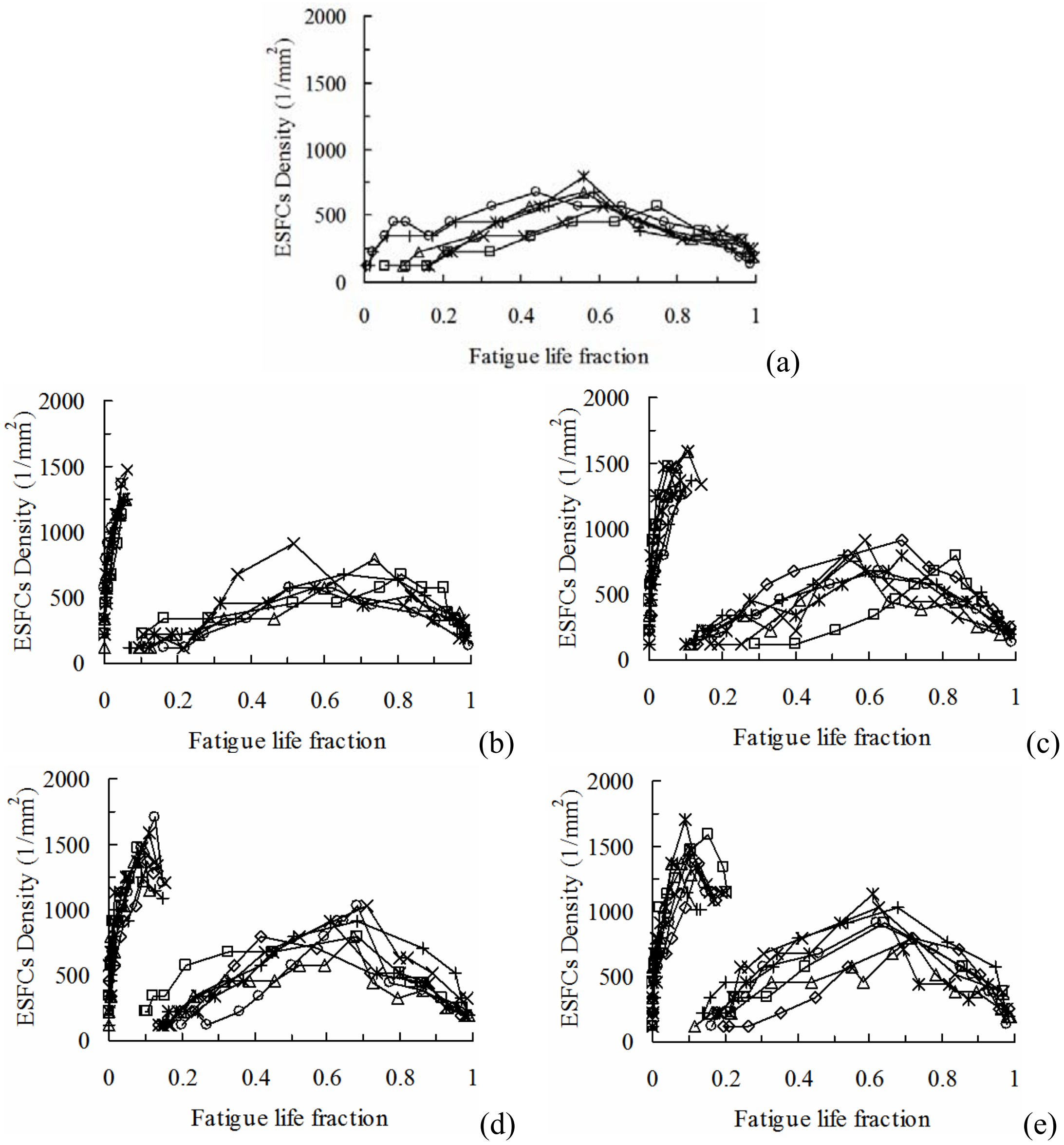

Figure 4. Effective short crack density for each group of LZ50 axle steel specimens repair times for specimens are (a) *f*=0.0, (b) *f*=0.3, (c) *f*=0.5, (d) *f*=0.6, and (e) *f*=0.7

3.3. Comparison of Fatigue Life

Fatigue life is the most direct indicator to reflect surface rolling effect. Table 5 gives the cyclic numbers before rolling, after rolling, and in total. To calculate the prolonged-life rate (defined as the ratio of total cyclic number to standard life), an average fatigue life of 137705 cycles, which was obtained from previous unrolled specimens fatigue tests[7], is cited as the standard life. It can be seen from the table that surface turning and rolling extends the fatigue life greatly than that of unrolled specimens. The prolonged-life rate increases from 4.49 to 6.41 with the advance of surface rolling time.

Theoretically, average fatigue life for S0.0 specimens to S0.7 specimens should be close to each other due to the same test stress amplitude. However, the choice of surface rolling time makes great difference in life extension effect. For example, the average life of initial rolled specimens (S0.0) is about 1.69 times the cyclic number after rolling of S0.7 specimens. The later surface treatment is performed, the slighter the life extension effect may be. Possible reasons are: Fatigue damage cumulated in material before surface turning and rolling can not be eliminated entirely. This residual damage gets more and more serious with delayed rolling time. Secondly, to remove existed surface cracks as thoroughly as possible, cutting thickness has to be increased with the postponement of rolling time. Thus, diameter and effective section of specimen are also reduced more seriously. Assume the same short cracks initiate in two specimens, local stress level for specimen with smaller diameter is relatively higher.

Table 5. Mean value of fatigue life and corresponding prolonged-life rate for each group of specimens

Repair time	Cyclic number before repair, cyc	Cyclic number after repair, cyc	Total cyclic number, cyc	Prolonged-life rate
f=0.0	--	882562	882562	6.41
f=0.3	41311	720580	761891	5.53
f=0.5	68852	627380	696232	5.06
f=0.6	82623	567379	650002	4.88
f=0.7	96393	522247	618640	4.49

4. Conclusions

(1) Ferrite grain boundary and rich pearlite banded structure are two primary micro-structural barriers to short fatigue crack growth for LZ50 axle steel. No matter surface rolling or not, dominant short crack growth data of all specimens exhibits deceleration twice in MSC stage due to above micro-structural obstacles. Growth rate of specimens after surface rolling is significantly slower than that of specimens before rolling.

(2) Effective short crack density for all five groups of specimens indicates the same overall trend, i.e., first rises then falls. Density after specimen rolling is much less. Surface rolling effect restrains the initiation of collective short cracks. However, this effect is weakened with the delay of rolling time.

(3) Surface turning and rolling to specimens prolongs the fatigue life greatly compared to the life of unrolled specimens. It is because turning cuts off possible existed short cracks in material surface and rolling improve the fatigue performance of new surface. But postponed implementation of surface rolling make the accumulated fatigue damage can not be eliminated thoroughly. In addition, increase of cutting thickness also increase the actual local stress.

In conclusion, for unrolled specimens, the earlier the surface treatment is performed, the better the collective effect of short cracks can be restrained as well as the longer the fatigue life of the material will be.

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