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Analyzing the mechanisms of fatigue crack initiation and propagation in CRH EMU brake discs

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ABSTRACT

A significant number of high-speed electric multiple units' (EMU) brake discs, manufactured from forged steel, showed thermal cracks during work and NDT. There exist three kinds of cracks on the friction surface; namely, the crackle, radial crack and circumferential crack. Macro-morphologies of the friction surface indicate that the cracks appeared in the interior and edges of the hotspots. Crack growth methods include the single crack propagation and multiple crack connectivity. A finite element analysis (FEA) was performed to determine temperature and stress distribution in the brake disc as well as to estimate stress distribution during braking. Simulation results indicate more significant residual, circumferential tensile stress on the external friction surface after emergency braking. The maximum residual circumferential tensile stress is 200 MPa after 300 km/h emergency braking. In addition, there is only the circumferential compressive stress on a section which is a certain distance from the exterior of the friction surface, and the distance depends on braking conditions. Therefore, not taking into account thickness reduction of the friction surface due to wear, it can be concluded that when the cracks run along the thickness direction to the specified distance, they will cease to run along this direction and begin propagating mainly in the direction of the radius. In addition, based on the simulation results, a measure was presented to prevent and inhibit the crack propagation.

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1. Introduction

Friction brakes are required to transform large amounts of kinetic energy into heat energy at the contact surfaces between brake discs and pads. CRH EMU wheel-mounted forged steel brake discs are exposed to heavy thermal and mechanical loadings and subjected to high thermal shock loading during routine braking and emergency braking. In fact, the distribution of high temperature zones caused by thermal shock loading is uneven on the friction surface during the heating and cooling steps of the braking action. After a series of braking cycles, the hotspots that exhibited signs of heating occurred on the friction surface as shown in Fig. 1. These hotspots have been investigated by many researchers over the years [1–5]. The material properties of the hotspots were changed, including the expansion coefficient, strength, hardness and so on [6]. Thermal crack occurred after several thermal cycles, contributing to the performance differences between the materials in different zones of the friction surfaces. The friction surfaces of the discs showed the presence of small cracks after a few thousand miles, as shown in Fig. 2. These cracks were clearly visible with the naked eye and divided into three types; namely, the crackle, radial crack and circumferential crack. The aim of the work presented here was to investigate deeper and understand the mechanisms of fatigue crack initiation and propagation on the friction surfaces. Fracture surface examination was done by means of

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Fig. 1. Hotspots on the friction surface.

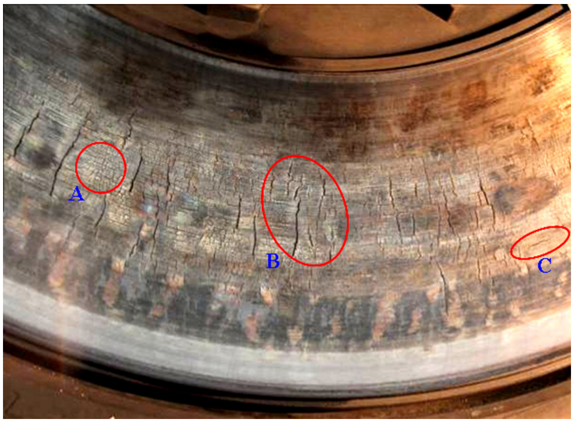

Fig. 2. Cracks on the friction surface (A) crackle, (B) radial crack and (C) circumferential crack.

scanning electron microscope (SEM) and X-ray energy dispersive spectroscopy (EDS). Additionally, finite element analysis was carried out.

2. Observation and discussion

2.1. Characteristics of the friction surface

Fig. 3 shows the local friction surface of the brake disc, which withstood a series of braking cycles and had been subjected to higher temperatures. During braking, the energy absorbed by the brake disc was dispersed into two kinds of action. A portion of the energy was discharged in crack propagation, and the rest elevated the temperature of the friction surface.

Through careful observation and analysis, inferences could be made from the photos of the local friction surfaces: the cracks generally initiated in the interior and at the edges of the hotspots; in addition, it has been reported (Ref. [7]) that it is necessary for crack propagation to absorb a certain amount of energy. In fact, the more thermal crack appears in the friction surface, the more energy crack propagation would consume. As a result, the hotspot phenomenon would gradually be reduced, as depicted in Fig. 3.

2.2. Breaking test

The plate samples, which were machined from the brake disc consisting of typically longer cracks, as shown in Fig. 4, were broken with an MTS-Sintech 65/G fatigue tester (Fig. 5). Observation of the fractures was done by means of fracture surface

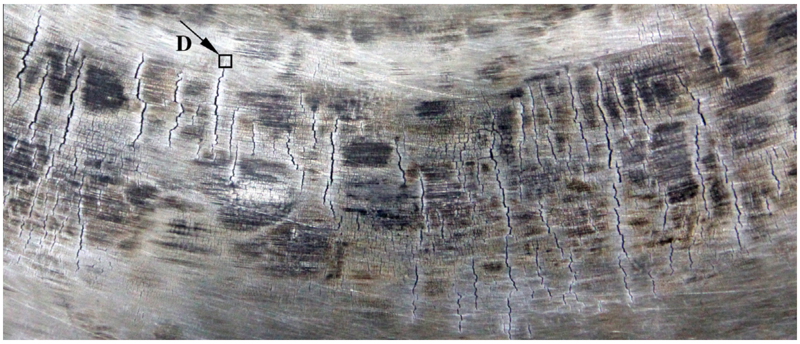

Fig. 3. Closeup view of the local friction surface.

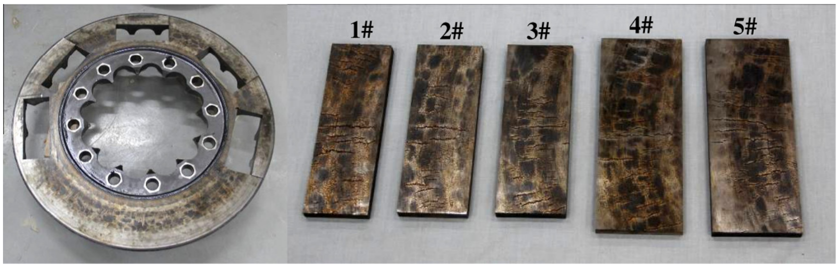

Fig. 4. Positions on the disc and shape of the three point bending samples.

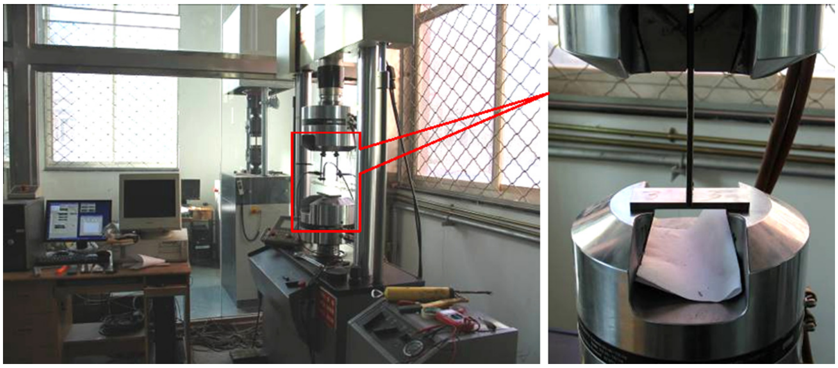

Fig. 5. MTS-Sintech 65/G test machine.

examination using a scanning electron microscope (SEM), and utilizing an X-ray energy dispersive spectroscopy (EDS) technique.

2.3. Macro-fractographic analysis

After crack fractures were produced through a breaking test, SEM analysis then revealed that radial propagation of the crack occurred faster than thickness propagation; furthermore, the cracks were propagated in a semi-elliptical shape through the thickness of the friction surfaces in accordance with a thermal fatigue mechanism [8,9]. Crack growth methods included the single crack propagation and multiple crack connectivity, as shown in Fig. 6, and the crack fracture in Fig. 7 showed both a fatigue propagation and a tear zone.

2.4. Micro-fractographic analysis

A magnification of the detail D taken from Fig. 3 was shown in Fig. 8 to pay more attention to the initiation point of the cracks. The material components were analyzed by means of X-ray energy dispersive spectroscopy. It was noted from Fig. 8

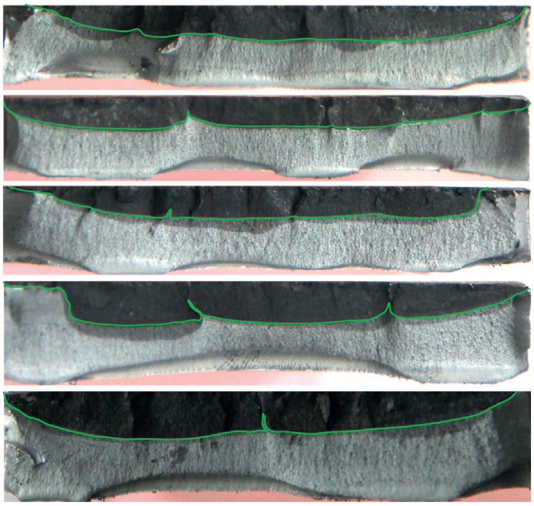

Fig. 6. Macro morphologies of the crack fractures.

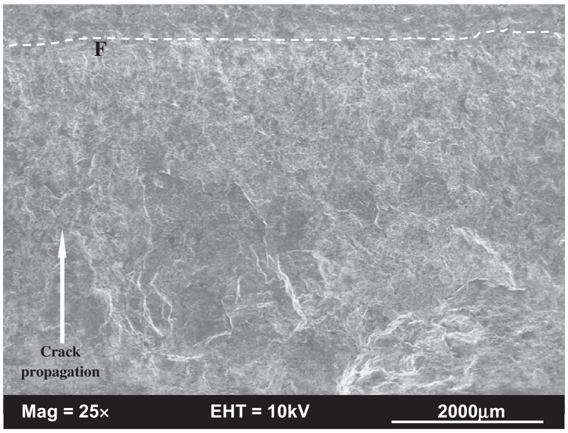

Fig. 7. SEM micrograph of the crack section.

that oxidation was present in the D zone. Fig. 9 showed the SEM micrograph of the F zone in Fig. 7. Some dimples in the tear zone were observed. In addition, Fig. 10 shows the SEM micrograph of the G zone in Fig. 9, and a significant amount of fatigue striations can be noted in this zone.

3. Analysis of simulation results and discussion

Taking into account the heat flux factor during the braking and cooling process, a transient FE technique was used. During the braking and cooling simulation, the different heat flux values were assigned to the element within the contact zone at regular intervals in the FE model. The location of the contact region at each interval was to be determined by the relative position of the disc and pad as the deceleration rate of the disc was known.

The thermal simulation was carried out to determine the temperature distribution throughout the disc during the braking and cooling process. The linear–elastic mechanical calculation was employed in order to estimate the circumferential stress once the temperatures were obtained and the displacement constraints were taken into account. The detailed conditions of the calculation are shown in Table 1.

The distribution of the temperature in the disc is given in Fig. 4. It can be seen that the temperature field of the disc during an emergency braking application has uneven and non-axisymmetric characteristics. Further, it is observed that the higher temperature zones were mainly located in the middle of the external friction surface. The maximum temperature, 751.736 °C, was located on the contact area between the brake disc and pad (see Fig. 11).

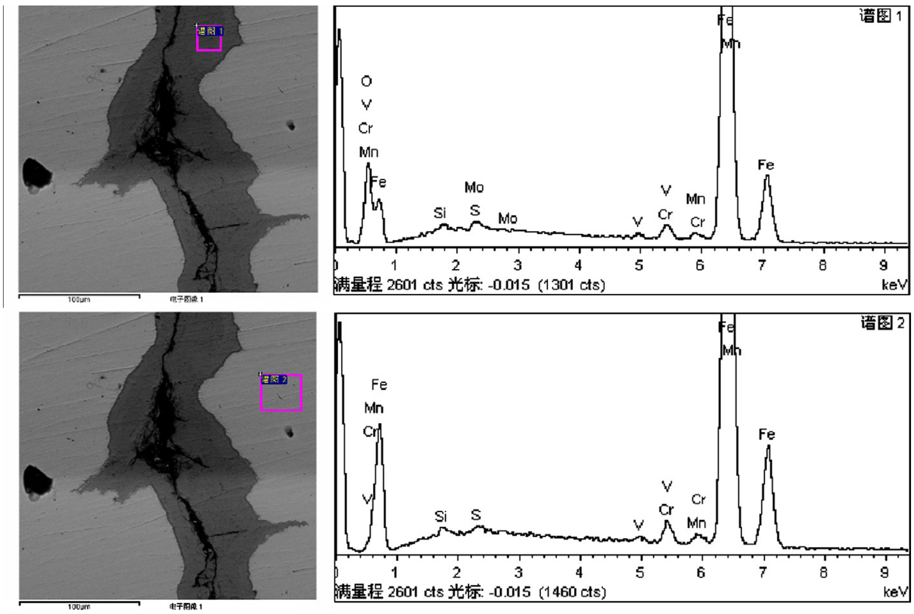

Fig. 8. X-ray energy dispersive spectroscopy in the D zone.

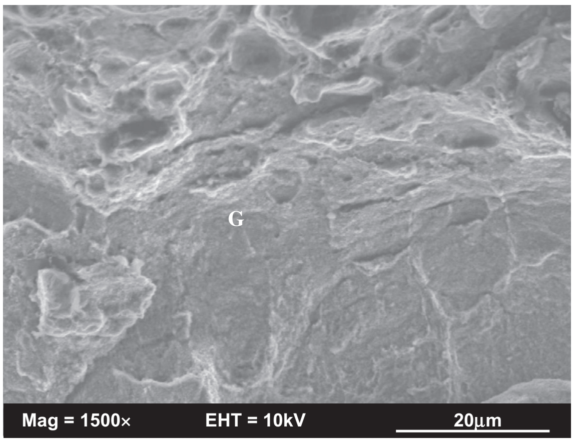

Fig. 9. SEM micrograph of the F zone.

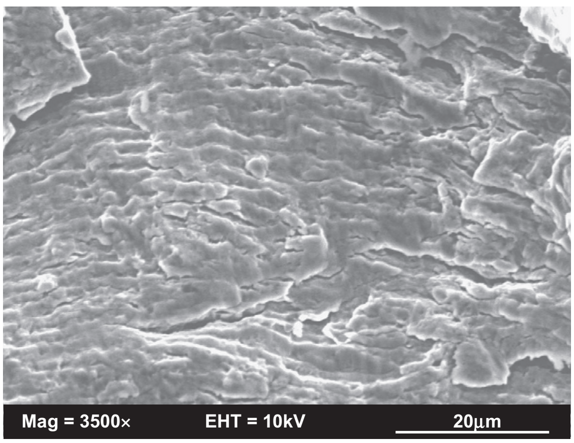

Fig. 10. SEM micrograph of the G zone.

Table 1
Emergency brake parameters.

Brake speed	Axle load	Brake pressure	Friction coefficient	Deceleration	Brake time	Brake distance
300 km/h	154,000 kg	30kN	0.265	0.755 m/s2	110.39 s	4600 m

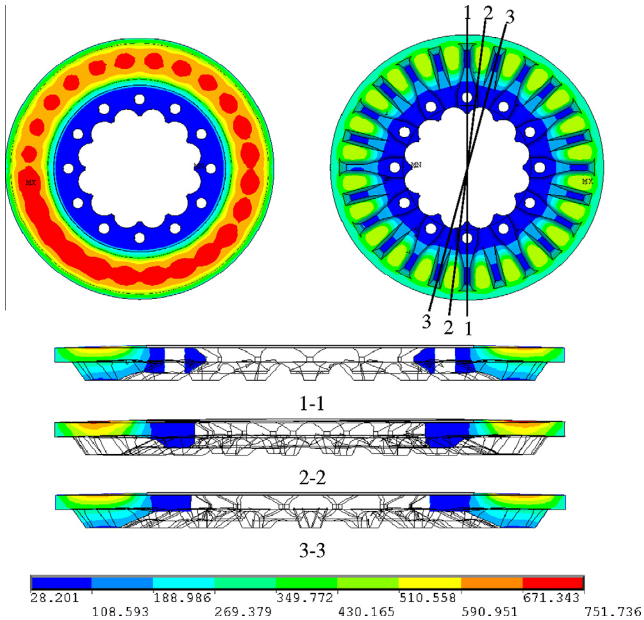

Fig. 11. Temperature distribution at the highest temperature moment (68 s) during 300 km/h emergency braking.

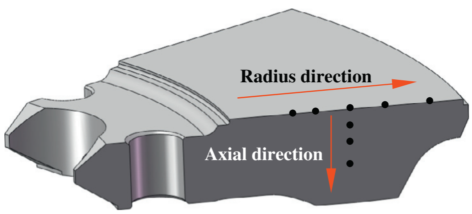

Fig. 12. Scheme of the temperature measuring points.

The four positions were chosen along the thickness direction, their distances from the friction surface being 0 mm, 5 mm, 10 mm, and 18 mm respectively, as shown in Fig. 12. Trends of circumferential stress versus time are shown in Fig. 13, which was obtained from the simulation results of the emergency braking.

Fig. 13 indicates that the stress characteristics in the disc were altered along the thickness orientation during the emergency braking and cooling process. Of special note was the curve marked 10 mm as its value was always negative during the braking and cooling process. This finding indicates that the circumferential stress was the compressive stress from beginning to end, and that compressive stress would prevent crack propagation; whereas the value of the curve marked 0 mm was negative during the early stage of the braking and cooling time, and then changed to positive for the remaining time. It can be illustrated that the plastic deformation generated on the friction surface created the tensile residual stress when the brake disc was cooling down. The maximum value of the tensile residual circumferential stress generated on the friction surface was 200 MPa after 300 km/h emergency braking and cooling and occurred on the external friction surface, as shown in Fig. 13.

Fig. 14 shows that the value of the curves was always negative. It indicates that the characteristics of the stress in the disc were unchanged along the thickness direction during the routine braking and cooling process, and the circumferential stress was the compressive stress from beginning to end. The maximum value of the circumferential stress that occurred on the friction surface was about 300 MPa during routine braking action. It was inferred that the alternating load condition between

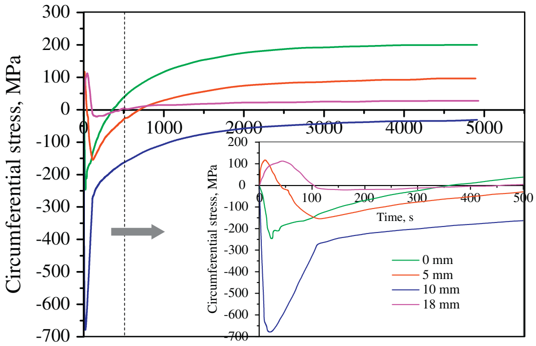

Fig. 13. Circumferential stress in different thickness positions under emergency braking.

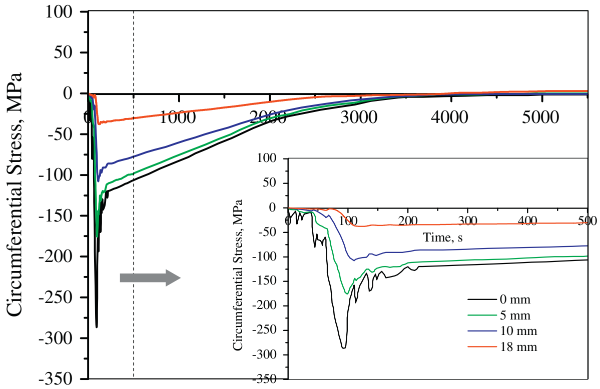

Fig. 14. Circumferential stress in different thickness positions under routine braking.

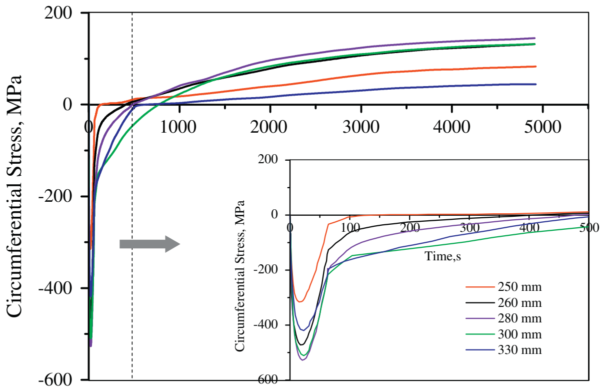

Fig. 15. Circumferential stress in different radius positions under emergency braking.

the circumferential tensile residual stress and compressive stress was applied on the external friction surface periodically and led to the fatigue crack initiation and propagation after the disc withstood a series of braking cycles.

Based on the above analysis, in order to reduce and inhibit the initiation and propagation of fatigue cracks, it was decidedly important to reduce or eliminate the circumferential residual stress in the brake disc. In order to achieve the above goal, after an emergency braking, a braking mode similar to a ramp brake with long distance and low pressure was carried out. In this braking mode, the temperature of the brake disc rises slowly and uniformly, the circumferential residual stress is reduced or eliminated, and the amplitude of the tension–compression cycle is reduced.

In addition, five positions were selected in the radius direction on the external friction surface, the radius values being 250 mm, 260 mm, 280 mm, 300 mm, and 330 mm respectively, as shown in Fig. 12. The treads of the circumferential stress

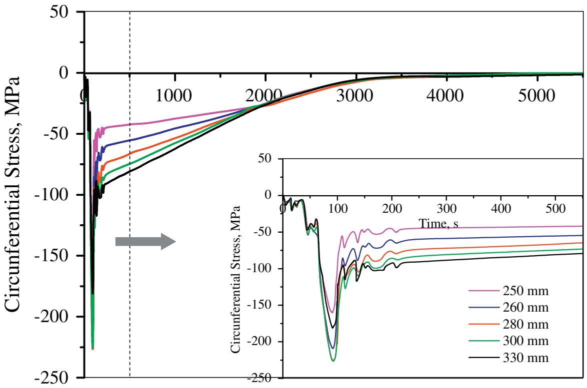

Fig. 16. Circumferential stress in different radius positions under routine braking.

versus time are shown in Figs. 15 and 16, which were obtained from the simulation results of the emergency braking and routine braking respectively.

Fig. 15 indicates that the residual tensile stress occurred on the external friction surface during the cooling, and its value was larger in the middle of the external friction surface. Fig. 16 demonstrates that the value of the curves was always negative during routine braking action. It indicates that the circumferential stress is the compressive stress from beginning to end. The maximum value of the circumferential compressive stress was about 250 MPa. It can be inferred that the fatigue crack initiation and propagation occurred firstly in the middle of the friction surface.

4. Conclusions

It can be inferred from observing the simulation results of the brake disc that:

(1) The cracks generally initiate in the interior and at the edges of the hotspots. The length of the thermal fatigue cracks is generated in two ways; namely, single crack propagation and multiple crack connectivity.
(2) With the cracks initiating and propagating, the hotspots on the friction surface are gradually reduced.
(3) During braking, the exterior of the friction surface is subjected to periodic tensile and compressive circumferential stress which leads to fatigue crack initiation and propagation.
(4) The ratio of the long to the short axis of elliptically shaped cracks increased gradually. Therefore, the failure of the forged steel brake disc is mainly attributed to the radial crack length over critical value; in addition, it is impossible for the cracks to run throughout the thickness of the friction surface.
(5) A brake model with long distance and low pressure could reduce the residual stress caused by a severe emergency braking, and could contribute to the delay restraint of the initiation and propagation of thermal fatigue cracks to some extent.

Acknowledgements

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