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Thermo-Mechanical Coupling Simulation of Disc Brake under Emergency Braking and Slow Braking Mode

Zhennuo Lei

School of Automotive Engineering, Shandong Jiaotong University, Jinan, 250357, Shandong, China

Keywords: Disc Brake; Finite Element Analysis; Heat-Machine Coupling; Temperature Field; Stress Field

Abstract: A three-dimensional thermo-mechanical coupling finite element model of a solid disc brake is established for a certain type of vehicle to analyze the thermo-mechanical coupling characteristics of the brake disc and the friction pad under emergency braking and slow braking. The temperature and stress fields of the solid disk brake are simulated under the two braking modes to obtain the distribution characteristics of the temperature and stress fields of the brake, and the interaction between the temperature and the equivalent force is discussed. The results show that the slow braking condition is more likely to cause the phenomena of elevated temperature and equivalent force than the emergency braking condition. In addition, a three-dimensional finite element model incorporating the thermal-mechanical coupling effect is developed for analyzing the transient behavior of solid disc brake systems under emergency and progressive braking conditions. The model embodies the coupled thermal stress interactions between the brake disc and the friction pad, and simulates the spatial and temporal evolution of the temperature and von Mises stress field during braking.

1. Introduction

At present, with the increase of car ownership in China, traffic safety problem attracts more and more attention from all walks of life. Data show that the braking performance of vehicles is directly related to road safety, especially in the environment of increasing vehicle density, improving braking system effectiveness has become an important technical breakthrough to reduce the risk of accidents. According to statistics, brake failure due to thermal fatigue accounts for 50% of all accidents [1-2].

In the study of brake thermal coupling, Lan Shiming simulates the thermal coupling under emergency braking conditions according to thermal coupling theory [3]. Fan Bo takes the ventilated disc brake as the research object, simulates the heat-mechanical coupling phenomenon under the emergency braking condition, and verifies the validity of the simulation results through bench experiments [4]. Wang Zhengguo et al [5] investigated the effect of groove distribution on the thermo-mechanical coupling characteristics and vibration behavior of brakes based on thermal-displacement transient analysis. Zhang Xuesong simulates and analyzes the coupling field of thermal and structural stresses in disc brakes under different material parameters, and derives the effects of each group of different material parameters on the braking process of the brake [6].

Karamoozian A and Ahmed G S et al [7-8] analyzed the effect of radial groove size and number on the surface temperature distribution of the brake disc. Belhocine A calculated the heat transfer coefficient of the brake disc as a function of time using hydrodynamic simulation [9]. Jaenudin J.J and Pi Y C studied the heat distribution on the brake disc using the finite element method to analyze the Factors affecting the heat distribution on the brake disk during emergency braking [10-11].

Thermo-mechanical coupling simulation of brakes under emergency braking conditions is only analyzed in the above literature. Less research is done on other braking conditions. In this paper, a simplified finite element model of a type of brake disc is established, and the thermal coupling characteristics of emergency braking and slow brake disc are simulated and analyzed. The influence of temperature and stress field of brake disc under different brake conditions is discussed.

2. Disk Brake Model Construction

2.1 Underlying assumptions

Based on thermal coupling theory, the basic hypothesis of finite element simulation of brake disc and friction lining material is established: brake disc and friction lining material are homogeneous isotropic materials; only heat conduction and heat convection effects are considered, but the influence of heat radiation is ignored; pressure distribution on friction backing plate is uniform; influence of material abrasion on braking process; friction pads is fixed and brake disk rotates counterclockwise. Friction plates are fixed when braking and the brake disk rotates counterclockwise. When braking, all frictional work is thought to be converted into frictional heat, regardless of the effect of material abrasion.

2.2 Three-dimensional modeling of disc brakes

Based on the solid disc brake of a car, the main structural parameters of the brake disc and friction pad, see Table 1. Use Space claim software to establish a three-dimensional solid model of the disc brake based on the measured parameters, see Figure 1.

Table 1. Main structural parameters of brake discs and friction pads

Structure	Outer radius/mm	Inner radius/mm	Total thickness/mm	Package angle/ °
Brake disc	151	76	20	360
Friction plate	136	85	8	63

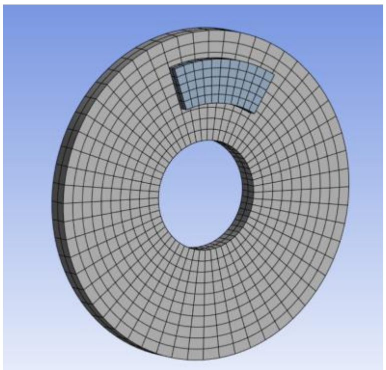


Figure 1. Three-dimensional model of solid disk brake

2.3 Material parameters

The brake disc materials are HT250 and the friction pad are resin-based composites. the mechanical and thermophysical properties of the two materials are shown in Table 2 and Table 3. The convective heat transfer coefficients between the friction pads and its surroundings is empirical value, and the convective heat transfer coefficients between the brake discs and its surroundings is the empirical formula [12].

Table 2. Main physical parameters of brake disc

temperature /℃	density /(kg/mm³)	modulus of elasticity /GPa	Poisson's ratio	linear expansion coefficient $/k^{-1}$	heat conductivity / $(W \cdot m^{-1} \cdot k^{-1})$	specific heat capacity / $(J \cdot kg^{-1} \cdot k^{-1})$
20	7200	105	0.3	4.39×10^{-6}	42.38	503
100	7200	95	0.3	11.15×10^{-6}	43.06	530
200	7200	90	0.3	12.84×10^{-6}	44.23	563
300	7200	90	0.3	13.58×10^{-6}	43.55	611

Table 3. Main physical parameters of friction plates

temperature /℃	density /(kg/mm³)	modulus of elasticity /GPa	Poisson's ratio	linear expansion coefficient $/k^{-1}$	heat conductivity / $(W \cdot m^{-1} \cdot k^{-1})$	specific heat capacity / $(J \cdot kg^{-1} \cdot k^{-1})$
20	1850	2.20	0.21	10×10^{-6}	0.9	200
100	1850	1.30	0.21	18×10^{-6}	1.1	1250
200	1850	0.53	0.21	30×10^{-6}	1.2	1295
300	1850	0.32	0.21	32×10^{-6}	1.5	1320

2.4 Braking mode parameter setting

In brake system research, emergency braking conditions are typically characterized by examining deceleration profiles of brake discs under unstable rotational speeds at specified loads. While such studies provide critical insights into brake behavior and friction material selection, real-world applications involve variable rotational speeds that exhibit distinct patterns depending on the braking mode. Two primary braking modes can be distinguished: emergency braking and gradual braking.

Under experimental emergency braking conditions, the brake disc demonstrates a rapid acceleration phase from 0 to 120 rad/s within 0.6 seconds, followed by an abrupt deceleration to complete rest over 2.57 seconds, resulting in a total braking duration of 3.17 seconds. In contrast, gradual braking conditions present a different operational profile: the disc initially climbs to 80 rad/s in just 0.1 seconds, then undergoes a prolonged deceleration phase lasting 23.9 seconds until full stop is achieved, yielding a significantly extended total braking time of 24 seconds.

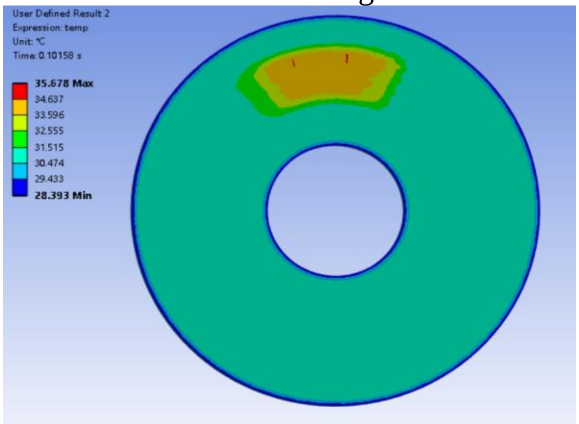
3. Simulation Results

3.1 Temperature distribution characteristics of brake disk under emergency braking condition

Thermal Analysis under Emergency Braking Conditions, the transient temperature distribution of the brake disc during emergency braking is presented in Figure 2. Analysis reveals a progressive temperature escalation during the braking sequence, reaching a peak value of 86.775℃. Notably, the disc maintains thermal dominance over the friction plate throughout the braking cycle, with this temperature differential being particularly pronounced during both initial engagement and final deceleration phases.

This thermal behavior can be attributed to dynamic frictional interactions between the components. During the initial high-speed phase (0-0.6s), the substantial relative velocity between disc and friction plate generates intense frictional heat flux, predominantly influencing the disc's thermal profile. As the system transitions to the deceleration phase (0.6-3.17s), reduced rotational velocity diminishes frictional heating while ambient convective heat transfer becomes increasingly significant, ultimately driving the temperature decline observed in later stages.

Critical examination of Figure 2 identifies the central annular region as the thermal focal point, consistently exhibiting maximum temperatures. This phenomenon stems from two synergistic factors: (1) direct interfacial contact with the friction plate establishing a primary heat generation zone, and (2) constrained convective cooling due to restricted airflow in the contact interface geometry. The combination of concentrated energy input and impaired heat dissipation creates this persistent thermal maximum region.



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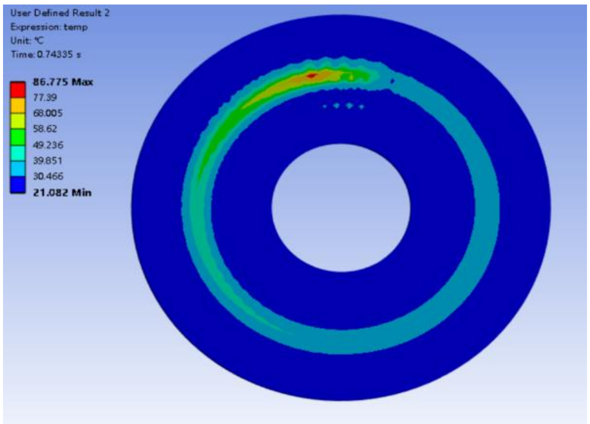

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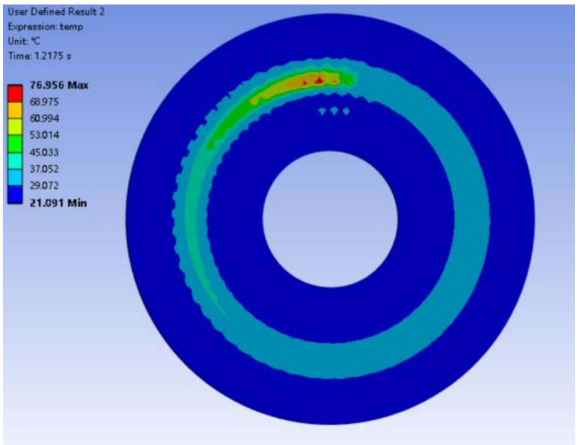

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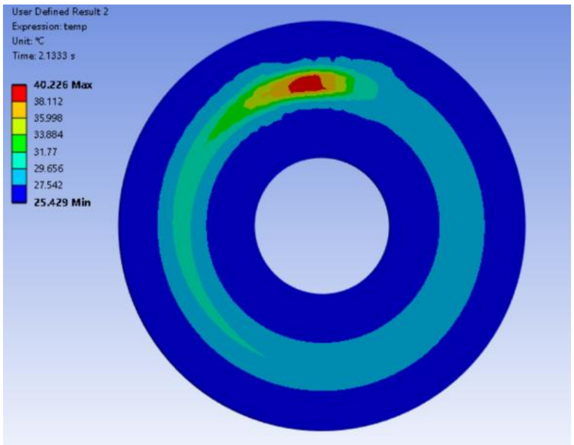

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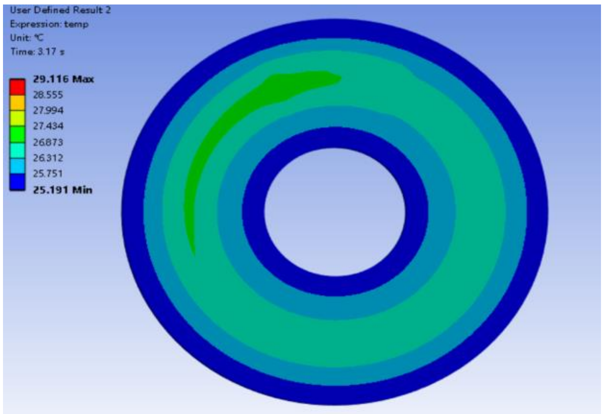


(e)3.17s

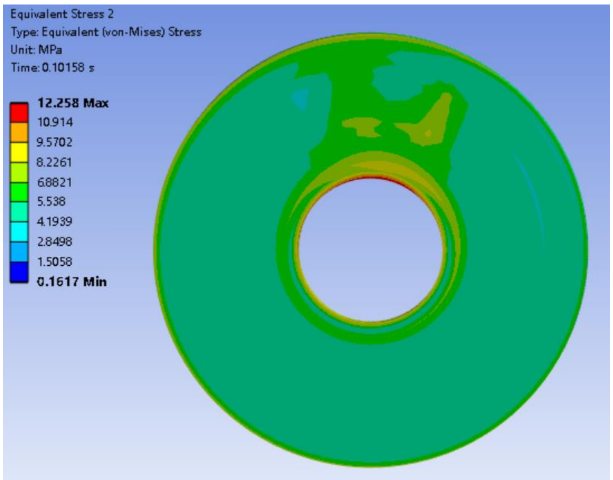
Figure 2. Brake disc temperature distribution characteristics

3.2 Stress Distribution Characteristics of Brake Disc under Emergency Braking Condition

Stress Distribution Analysis Under Emergency Braking, Figure 3 details the evolution of equivalent stress (von Mises stress) in the brake disc during emergency braking. The results indicate a gradual increase in stress magnitude over time, reaching a maximum value of 39.766 MPa. Throughout the braking process, the central region of the disc consistently exhibits higher stress concentrations compared to its peripheral areas.

This spatial stress pattern directly correlates with the disc's thermal behavior. As previously established (Figure 2), the central region experiences the highest temperatures due to direct frictional contact with the brake pad. The resultant thermal expansion and material property variations at elevated temperatures amplify mechanical stresses in this critical zone. During the later braking phase, stress magnitudes decrease in tandem with diminishing frictional heat flux, demonstrating the coupled thermomechanical response of the system.

A notable temporal discrepancy is observed between peak temperature and peak stress occurrences: the maximum stress manifests slightly later than the temperature peak. This hysteresis effect arises from the time-dependent nature of thermo-mechanical coupling, where stress redistribution lags behind thermal transients due to delayed heat transfer and temperature-induced material deformation.



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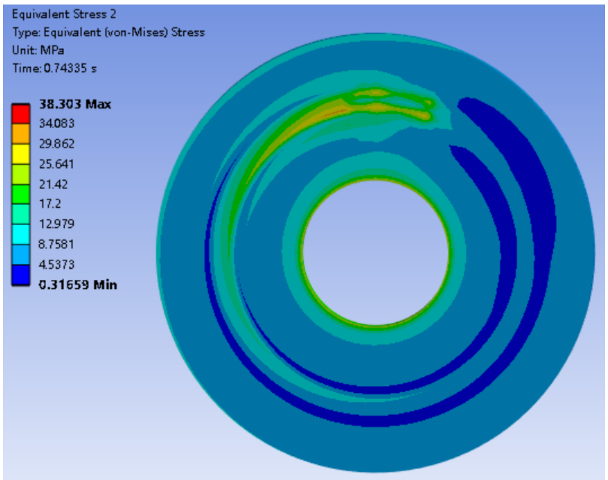

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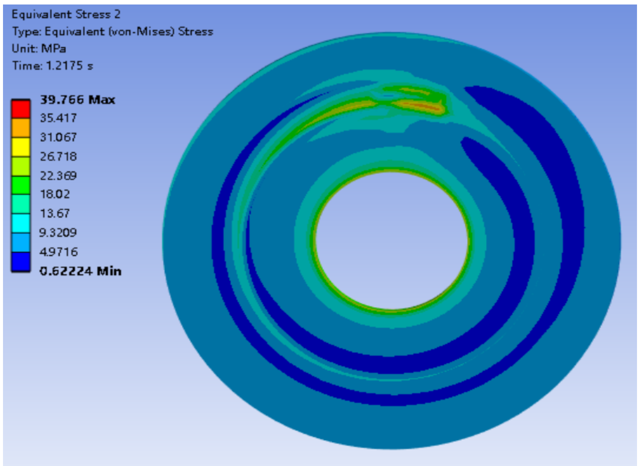

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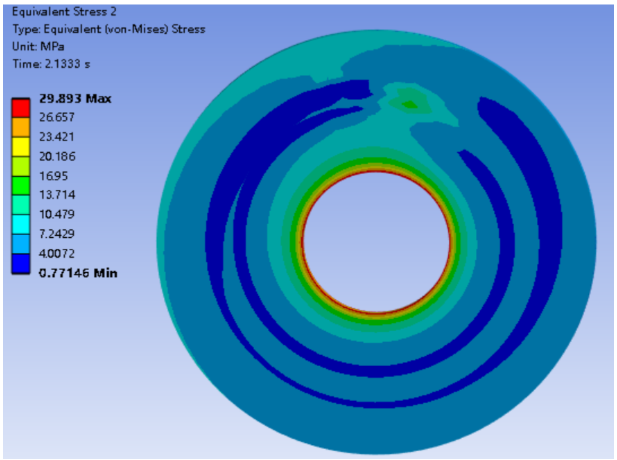

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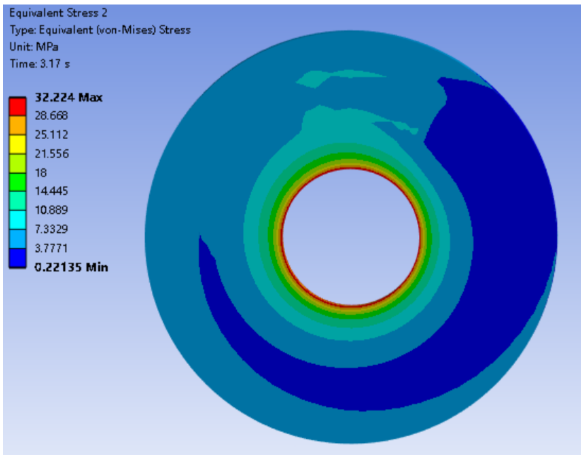


(e)3.17s

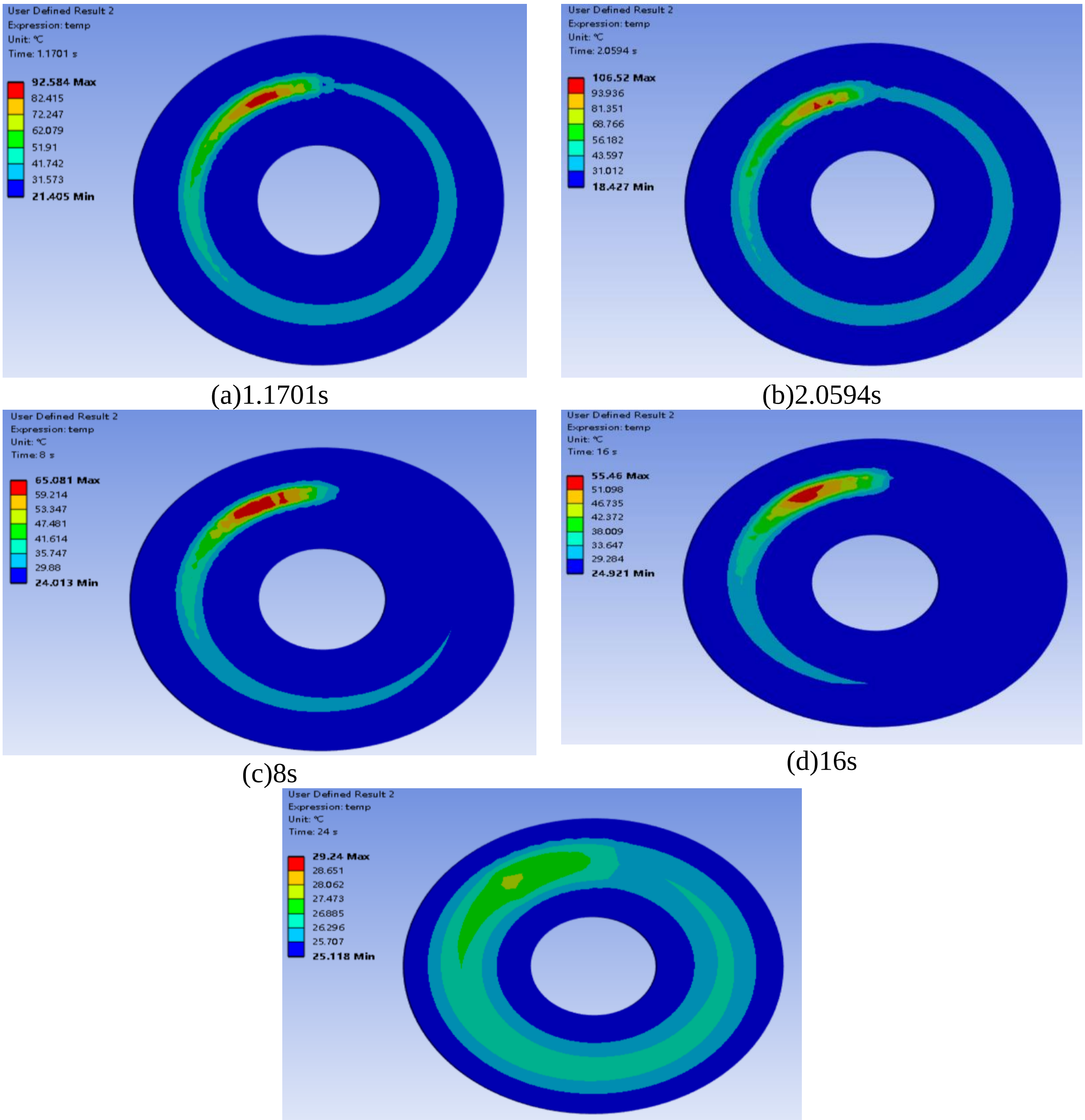
Figure 3. Brake disc stress distribution characteristics

3.3 Temperature Distribution Characteristics of Brake Disc under Slow Braking Condition

Thermal Characteristics during Gradual Braking, The temporal temperature distribution of the brake disc under slow braking conditions, as detailed in Figure 4, exhibits a characteristic progression. Frictional heating induces a monotonic temperature rise across the disc surface, establishing a radial thermal gradient with maximum temperatures concentrated at the friction interface. This thermal maximum forms an annular high-temperature zone that propagates outward as braking progresses.

The observed thermal behavior arises from two competing mechanisms: sustained thermomechanical coupling at the disc-pad interface during initial braking phases, and progressive heat dissipation through convective transfer with ambient air in later stages. As disc rotational velocity diminishes, frictional heat generation decreases significantly, allowing ambient cooling effects to dominate during the final braking period. Notably, the central annular region retains thermal prominence throughout the process due to persistent interfacial contact and constrained convective cooling.

This temperature-stress interdependence demonstrates the critical role of braking kinematics in governing transient thermal loads, where extended braking duration permits gradual thermal equilibration distinct from emergency braking scenarios.



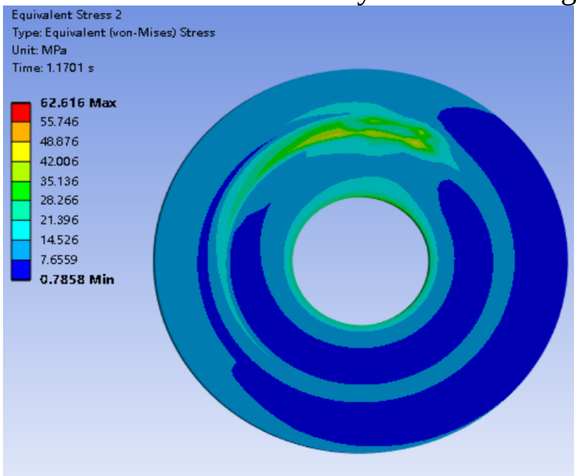
(a)1.1701s (b)2.0594s (c)8s (d)16s (e)24s

Figure 4. Brake disc temperature distribution characteristics

3.4 Stress Distribution Characteristics of Brake Disc under Slow Braking Condition

Stress-Temperature Interdependence during Gradual Braking, Figure 5 documents the temporal evolution of von Mises equivalent stress in the brake disc under slow braking conditions. The stress distribution exhibits a strong correlation with the temperature field evolution (Figure 4), sequentially measuring 62.616, 64.215, 42.082, 36.898, and 36.023 MPa. A distinct stress peak of 64.215 MPa occurs at 2.0594 s, followed by progressive stress relaxation.

This mechanical response directly mirrors thermal behavior through distinct phases. During the initial 2.0594 s, intensive frictional heating at the disc-pad interface generates rapid temperature escalation, inducing corresponding thermal stress amplification through constrained thermal expansion. Post-peak stress reduction coincides with declining frictional heat flux, as reduced disc rotational velocity diminishes energy input. Concurrent convective heat transfer to ambient air further accelerates stress decay in later braking stages.



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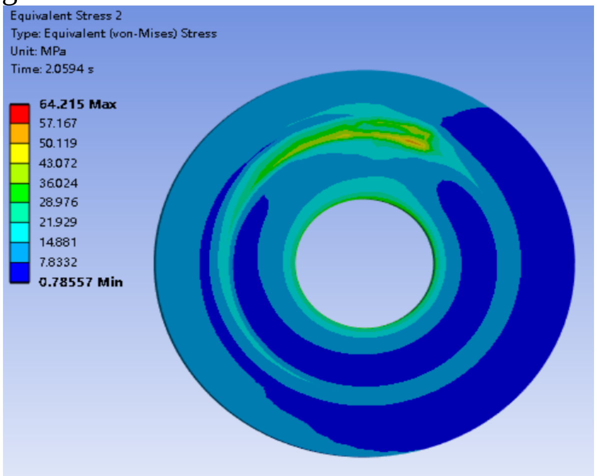

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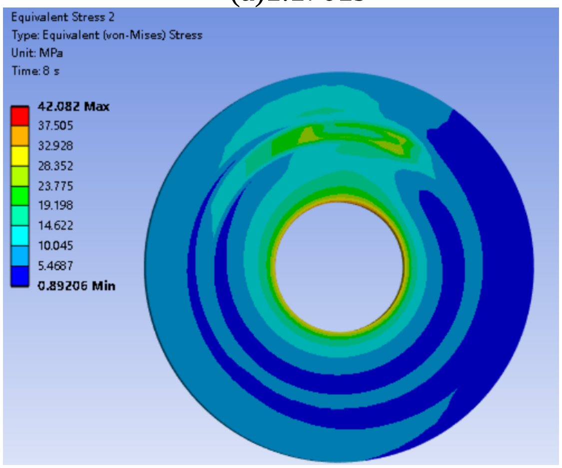

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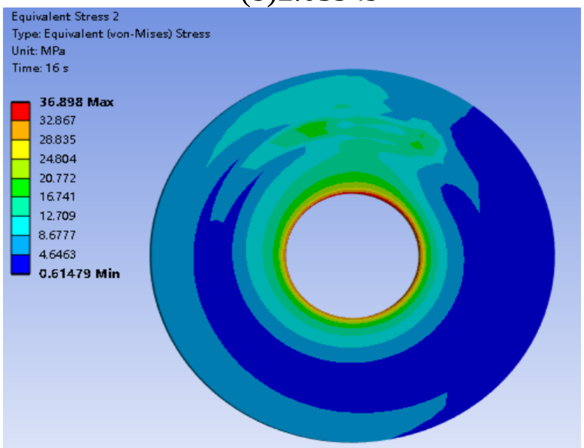

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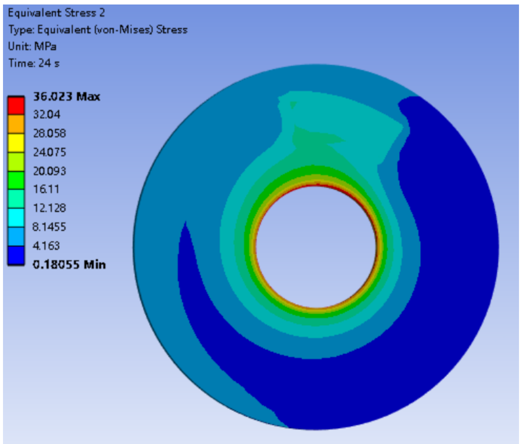

(e)24s

Figure 5. Brake disc stress distribution characteristics

4. Conclusion

This study employs a thermo-mechanical coupling analysis framework to investigate brake system behavior under two braking modes: emergency (high-intensity) and gradual (prolonged). The computational model resolves the interdependent thermal and stress fields, systematically examining transient temperature distribution patterns and von Mises stress evolution and the following conclusions are obtained:

(1) Brake systems exhibit distinct thermomechanical coupling characteristics under varying braking regimes, with temperature-mechanical load relationships demonstrating non-linear interdependencies. The establishment of condition-specific thermomechanical interaction profiles provides critical theoretical foundations for addressing thermal fatigue challenges, as comprehensive understanding of these coupled behaviors enables precise prediction of energy dissipation patterns and stress localization phenomena across operational scenarios.

(2) Emergency braking conditions, characterized by higher initial speeds and shorter durations, generate concentrated thermal accumulation that induces abrupt stress surges. In contrast, prolonged gradual braking enables progressive temperature-stress escalation through sustained low-intensity energy transfer. This operational contrast reveals that extended braking durations amplify cumulative thermal-mechanical effects despite lower instantaneous loads, providing critical insights for brake system design optimization focused on duty-cycle-specific durability enhancement.

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