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Thermal analysis for brake disks of SiC/6061 Al alloy co-continuous composite for CRH3 during emergency braking considering airflow cooling

JIANG Lan[1], JIANG Yan-li[2], YU Liang[2], SU Nan[1], DING You-dong[1]

1. School of Materials and Metallurgy, Northeastern University, Shenyang 110819, China;
2. Key Laboratory of New Processing Technology for Nonferrous Metals and Materials, Ministry of Education, Guilin University of Technology, Guilin 543004, China

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Abstract: The mass of high-speed trains can be reduced using the brake disk prepared with SiC network ceramic frame reinforced 6061 aluminum alloy composite (SiC_n/Al). The thermal and stress analyses of SiC_n/Al brake disk during emergency braking at a speed of 300 km/h considering airflow cooling were investigated using finite element (FE) and computational fluid dynamics (CFD) methods. All three modes of heat transfer (conduction, convection and radiation) were analyzed along with the design features of the brake assembly and their interfaces. The results suggested that the higher convection coefficients achieved with airflow cooling will not only reduce the maximum temperature in the braking but also reduce the thermal gradients, since heat will be removed faster from hotter parts of the disk. Airflow cooling should be effective to reduce the risk of hot spot formation and disc thermal distortion. The highest temperature after emergency braking was 461 °C and 359 °C without and with considering airflow cooling, respectively. The equivalent stress could reach 269 MPa and 164 MPa without and with considering airflow cooling, respectively. However, the maximum surface stress may exceed the material yield strength during an emergency braking, which may cause a plastic damage accumulation in a brake disk without cooling. The simulation results are consistent with the experimental results well.

Key words: finite element method; brake disk; co-continuous SiC/6061 composite; thermal analysis; airflow cool

1 Introduction

Lightweight is one of the key technologies for the high-speed trains. Unsprung weight can be reduced by using SiC/Al brake disk, so as to reduce the weight of high-speed trains. Comparing to iron and steels, SiC/Al composite has larger linear expansion coefficient and lower strength at high temperature, which increases the thermal damage tendency and limits the speed range of SiC/Al brake disks [1]. Recently, the co-continuous metal–ceramic composites have been applied widely to dry friction and wear applications since they can effectively enhance the tribological performance of the materials [2,3]. Since the SiC continuous network structure ceramics are a very promising material for high temperature structural applications and reinforcement in the SiC/6061 alloy composite materials, the composites have excellent mechanical properties and friction behavior, and can be used as the brake disk material [4,5]. In our previous work, the co-continuous SiC/Al alloy composites (SiC_n/Al) consisting of two interpenetrating continuous networks, Al alloy and SiC ceramic, were prepared [5,6]. It is well known that the main problem of braking and stopping a high-speed train, such as China Railway High-speed 3 (CRH3) system, is the great input of heat flux into the disk in a very short time. High temperature can cause a fall in friction coefficient, or fade, and increased wear of both discs and pads [7]. Both fade and increased wear are affected by local thermal distortions of the disc, which can lead to macroscopic hot spots (MHS) [8]. These MHSs are amongst the most dangerous phenomena in brakes, since they are associated with high thermal gradients. The consequent stress fields can lead to low cycle fatigue of the discs, cracking, and even catastrophic failure [9]. For these reasons, brake discs are often designed with slots or holes to create turbulence as they rotate, and thus to

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Corresponding author: JIANG Lan; Tel: +86-24-83681325; E-mail: jianl@smm.neu.edu.cn
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enhance convective heat transfer to the air [10]. The design constraints on the discs make it difficult to optimize every aspect of their design simultaneously, since it is desirable to optimize the weight and stiffness of the discs as well as their heat capacity and heat transfer capability, which leads to conflicting design requirements. The methods solving brake disk optimization concentrated on finite element method [11,12], approximate integration method [13,14], Green's function method [15] and Laplace transformation method [16], etc. The former three methods are numerical solution methods and are of low relative accuracy. For example, finite element method can solve the complicate heat conduction problem, but the accuracy of computational solution is relatively low, which is affected by mesh density, step length and so on. Though the Laplace transformation method is an analytic solution method, it is difficult to solve the equation of heat conduction with complicated boundaries. In fact, the temperature gradient and thermal stress of the brake disk are affected by the airflow through and around it. However, seldom calculations consider cooling with wind during the braking process. Therefore, the analytic solution called finite element (FE) and computational fluid dynamics (CFD) methods was adopted [17], because it is suitable for solving the problem of non-homogeneous transient heat conduction with airflow cooling.

This work was focused on the temperature and thermal stress analysis of the co-continuous SiC_n/6061 Al alloy composite (SiC_n/6061 Al) brake disk of CRH3 under centrifugal and thermal load during emergency braking considering airflow cooling, with the help of finite element calculation software. The airflow through and around the brake disk was analyzed [18]. The multi-contact elastic-plastic thermal-mechanical coupling model of disc brake was established in order to investigate the thermal-mechanical coupling problems. This provides the methods for the research on the thermal damage and structural design of the brake disk. The heat transfer coefficients considering convection and radiation were calculated and later used as a boundary condition in thermal numerical analysis using the Solidwork2012 Flow software package [19].

2 Modeling for calculation

The SiC_n/6061 Al composite was obtained by infiltration of molten 6061 Al alloy (0.40%−0.80% Si, 0.70% Fe, 0.15%−0.40% Cu, 0.15% Mn, 0.80%−1.20% Mg, 0.04%−0.35% S Cr, 0.25% Zn, 0.15% Ti, balance Al) into SiC network ceramic by vacuum-pressure casting process [20]. The SiC continuous network structure ceramic preforms were prepared by the porous polyurethane coated with large amounts of aqueous reactant containing *α*-SiC power (purity>99%, d_{50}=1.5 μm). The microstructure of SiC_n/6061 Al is shown in Fig. 1. The bright phase is the 6061 Al alloy matrix, and the dark phase is the SiC network. The models of the SiC_n/6061 Al brake disk for CRH3 high-speed train are shown in Fig. 2. The white part shown in Fig. 2(a) is the 6061 Al alloy matrix for brake disk. The black parts shown in Fig. 2(b) are SiC_n/6061 Al alloy composites which are embedded in the disk. In this analysis the brake disk without wear model was considered. The basic dimension of the brake disk is shown in Fig. 2(d). The brake disk has 22 cooling vanes equally spaced, which enables the usage of symmetry with a basic angle of 15°.

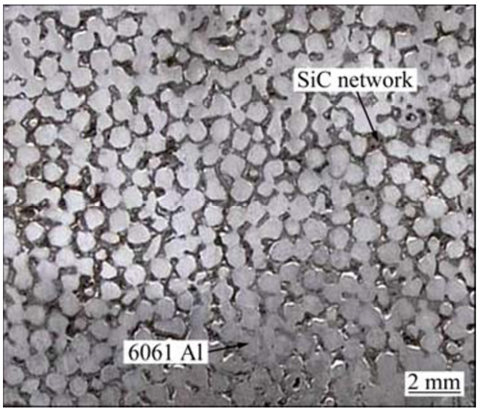

Fig. 1 Microstructure of SiC_n/6061 Al alloy composites

3 Calculation of cooling factors

3.1 Flow calculation boundary

The airflow through and around the brake disk was analyzed using the Solidwork2012 simulation software package. The heat transfer coefficients considering convection and radiation were calculated and organized in such a way that they could be used as a boundary condition in thermal analysis. The averaged heat transfer coefficients at a flow rate of 7.85 L/s, and an angle of 90°, for the nozzle-to-plate spacing H/D values of 3, 6 and 10 were applied in the calculation [21]. The brake disk model for calculation is shown in Fig. 3. A three dimensional model of the whole was chosen for airflow cooling numerical calculation, with size of 1200 mm × 1200 mm × 500 mm. The axisymmetric eight-node isoparametric elements were used for the finite element analysis of the model. To allow the gradient of the variables at the interfaces and boundaries, the finer mesh near the interfaces of disk brakes was adopted using the mapping function. The rest of the model was more