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ScienceDirect
Procedia Engineering 2 (2010) 679–685
Procedia Engineering
www.elsevier.com/locate/procedia

Fatigue 2010

Thermal fatigue evaluation of cast iron discs for railway vehicles

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Received 22 February 2010; revised 9 March 2010; accepted 15 March 2010

Abstract

Thermal fatigue of brake discs for railway vehicles has been a troublesome problem since the advent of disc brake. To develop cast-iron brake discs with high heat resistance to thermal shock loading, three candidate materials with different components were developed. Main components of the cast irons are Fe, C, Si, Mn, Ni, Cr, Mo, Cu and Al. Mechanical and thermal properties were measured. Then thermal fatigue tests were carried out by a thermal fatigue test equipment developed by the authors. The possible temperature range of the equipment is 20~1500 °C. Cylindrical solid specimens $\phi 20 \times 80$ mm were heated by an induction coil and cooled in water. At an interval of 20~30 thermal cycles, the surfaces of the specimens were examined with an optical microscope to check thermal cracks. To quantify the total length of cracks an image analyzing program that can measure the length of cracks from micrographs was developed. It was found the fatigue lifetime of cast iron can be elongated by regulating composition and metallurgical structures.

Keywords: Brake Disc; Cast Iron; Railway; Thermal Crack

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1. Introduction

Brake disks of rolling stock are exposed to heavy thermal and mechanical loadings during braking, and lots of thermal cracks occur on the surface of the disks. These thermal cracks may cause serious accidents, deterioration of brake performance and increase of maintenance costs due to frequent exchange of friction materials. Therefore, engineers and researchers have tried to develop materials with high resistance to thermal cracks. Under thermal shock loading as in brake discs, thermal cracks occur after several thermal cycles. So, crack propagation characteristic decides the lifetime of brake discs. Sakamoto and Hirakawa [1] developed forged steel discs mounted on wheels for Shinkansen trains. They used fracture toughness and stress intensity factors as parameters to select optimal candidate steels. They showed that thermal crack initiation is not influenced much by material characteristics. Yamabe et al. [2] developed brake discs for trucks with high thermal strength. They used grey cast iron with nickel. And they showed that cerium inoculation is effective to increase the number of graphite in microstructure and that thermal fatigue strength is proportional to the graphite number. They used a pin-on-disc type

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doi:10.1016/j.proeng.2010.03.073

wear tester. In case of rolling mill cylinders, turbine blades, nuclear reactor components, etc., thermal cracks are often related with high cycle thermal fatigue. Maillot et al. [3] studied thermal fatigue of AISI 304L and 316LN type stainless steel by using a thermal fatigue test device which uses direct current for heating and water for cooling. They quantified surface crack lengths and density by image analysis. The main objective of this study is to develop disk materials with high heat resistance, in other words, long thermal fatigue life. For this purpose, first of all, we developed a thermal fatigue test equipment which is composed of a PC, a controller, an induction heater and a chiller. The possible temperature range is 20~1500 °C. It takes about 50~100 seconds for a thermal cycle. Cylindrical specimens of diameter 20 mm were heated by the induction heater and cooled in water. After each thermal cycle, the surfaces of the specimens were examined with a microscope to see whether thermal cracks generated or not. After a few thermal cycles lots of thermal cracks occured. To quantify the thermal cracks a program that can measure the length of cracks from microscopic photographs was developed. Using this program we could easily measure the total length of all surface cracks on the micrographs and evaluate the propagation characteristic of cracks and thermal resistance.

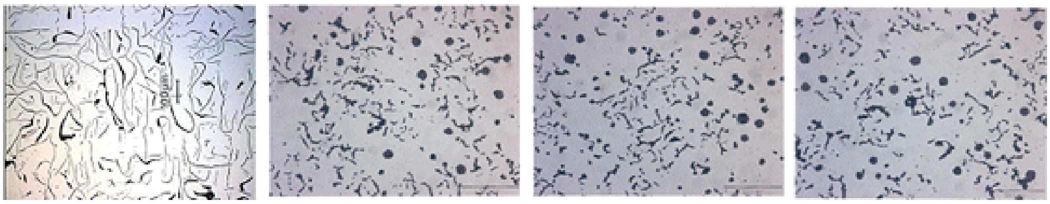
2. Materials and thermal fatigue tests

2.1. Materials

To develop high heat-resistant castings for brake discs a variety of elements such as Cr, Mo, Ni, etc. have been tried [4]. We also tried similar elements [5]. In Table 1 are shown three new candidate materials with different components and a conventional disc material (Conv.). The chemical compositions were analyzed by a spectrometer. Micrographs of the castings are shown in Fig. 1. The shape of graphite for the conventional brake is flake. For B, C and D material almost all graphite is compact vermicular. Some spherical graphite is scattered. To obtain vermicular graphite, Mg was added. Iron scraps were melted in an electric furnace at temperature of 1500-1550 °C. Sand molds were bound by furan resin. FeSi type inoculants were added. The solidified metals were kept in the sand molds until the temperature of the castings decreased to 350 °C. At this temperature, the molds were broken and the castings were air-cooled. Microstructural characteristics were analyzed according to ISO 945 [6] and are shown in Table 2. The elongation, hardness and tensile strength values shown in Table 3 are the average values of several measured data. In the order of B, C and D, hardness and tensile strength increase, but elongation rate decreases. It is mainly due to the difference of the contents of Ni, Cr and Mo. It is found the compressive strengths are much higher than the tensile strengths. This is known to be characteristic of cast iron.

Table 1. Chemical compositions (Wt. %)

Type	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Mg
Conv.	3.13	2.05	0.71	0.041	0.018	0.3	-	0.8	-	-
B	3.79	2.39	0.419	0.039	0.013	0.353	0.419	0.222	0.284	0.016
C	3.75	2.41	0.401	0.04	0.013	0.353	1.05	0.403	0.433	0.015
D	3.77	2.33	0.393	0.04	0.014	0.341	1.01	0.534	0.549	0.015



(a) Material Conv. (b) Material B (c) Material C (d) Material D

Fig. 1. Forms and distribution of graphite (×100)

Table 2. Results of microstructural investigation

Type	[1]P+G	[2]F	[3]NGR	[4]GM	[5]GD	[6]NG
Conv.	94.0	0	276	I	A	259
B	48.2	51.8	233	III	E	185
C	63.6	36.4	247	III	E	234
D	75.0	25.0	254	III	E	212

[1] **Perlite + Graphite percentage (%)**

[2] Ferrite percentage (%)
[3] Number of Grain (EA/cm^2)
[4] Graphite Morphology classification [6]
[5] Graphite Distribution classification [6]
[6] Number of Graphite (EA/mm^2)

Table 3. Mechanical properties of materials

Type	Tensile strength (N/mm^2)	Tensile Elongation (%)	Compressive Strength (N/mm^2)	Hardness (HBW 10/3000)
Conv.	275.0	0.11	693.2	220
B	414.0	3.1	688.4	179
C	483.4	2.1	784.1	209
D	499.6	1.2	824.2	215

2.2. Thermal fatigue tests

We developed a thermal fatigue test equipment (Fig. 2) which is composed of a PC, a controller, an induction heater and a chiller. Tests are controlled and monitored on a personal computer. The possible temperature range is 20~1500°C. Fig. 3 shows an example of thermal loading cycles. It is found the temperature cycles are consistent and reproducible. Temperatures are measured by a thermocouple. The induction heater increases very quickly the temperature of specimens. Cylindrical specimens of diameter 20 mm (Fig.4) move up and down by the air cylinder. They are heated by the induction heater coil in the upper position and cooled in water in the lower position. For the thermocouple to follow the temperature variation of the specimens, the specimens were heated slowly. It took 84 seconds for heating and 18 seconds for cooling. The cooling water was kept at a constant temperature, 25 °C by the chiller. After every several thermal cycles, the surfaces of the specimens were examined with an optical microscope to check whether thermal cracks were generated or not. 5 micrographs at 5 different positions were taken on each specimen surface. Each micrograph covers 4.48×3.59 mm^2. After a few thermal cycles lots of thermal cracks were produced. To quantify the cracks an image analyzing program that can measure the length of cracks from micrographs was developed. Using this program we can easily measure the total length of all surface cracks on the microscopic photographs and evaluate the propagation characteristics of cracks and thermal resistance.

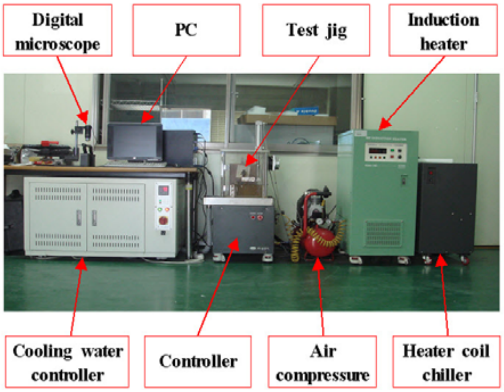


Fig. 2. Thermal fatigue test equipment

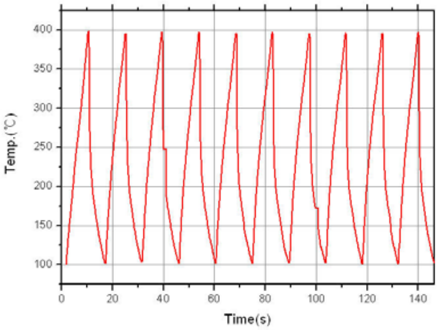
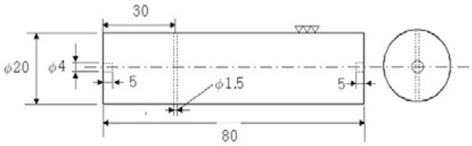
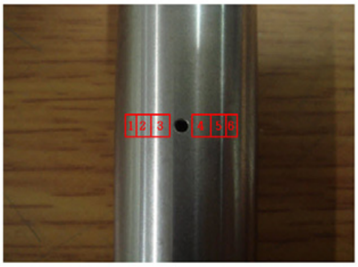


Fig. 3. Temperature cycles.



(a) Specimen for thermal fatigue test

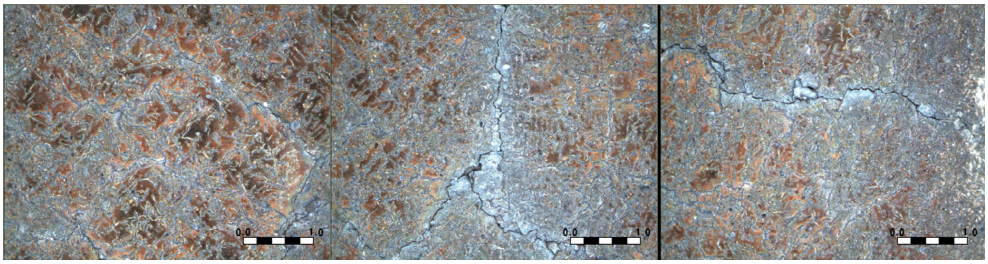


(b) Crack observation points on specimen

Fig. 4. Specimens and crack observation points

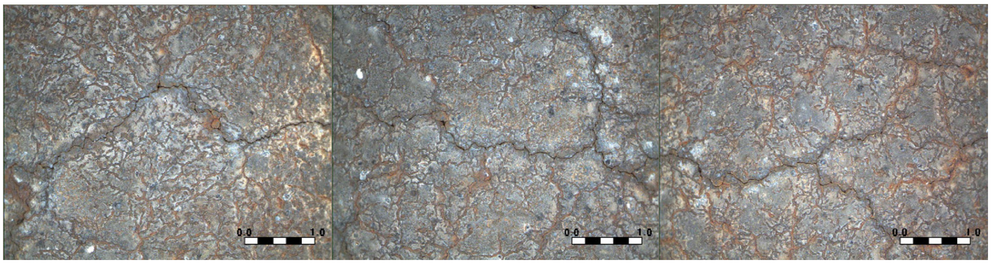
3. Test results

The characteristics of crack initiation and propagation depend on the observation positions of specimens, because the specimens are not homogeneous, not heated and not cooled uniformly. We examined 5 spots on the surface of each specimen and measured total crack length on each spot. Fig. 5 shows the development of thermal cracks after 780 thermal cycles in the specimen made from a conventional disk in service use. Figs. 6-8 show the results for material B, C and D respectively. Fig. 9 shows the total crack length of 5 spots. It is found the candidate materials are more resistant to thermal shock loading. In the case of conventional material, the initiation life of thermal fatigue is shorter than the material B, C and D. Fig. 10 shows the crack propagation rates.



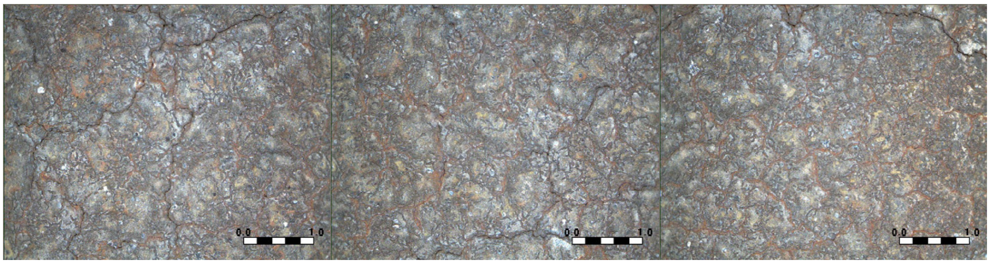
(a) Observation spot 1 (b) Observation pot 2 (c) Observation spot 3

Fig. 5. Cracks in material Conv. after 780 thermal cycles



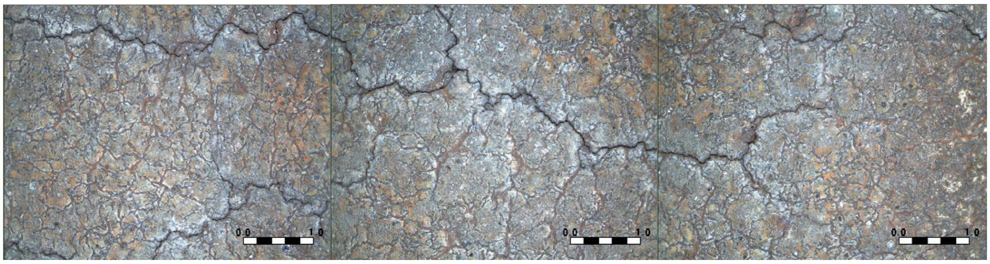
(a) Observation spot 1 (b) Observation pot 2 (c) Observation spot 3

Fig. 6. Cracks in material B after 780 thermal cycles



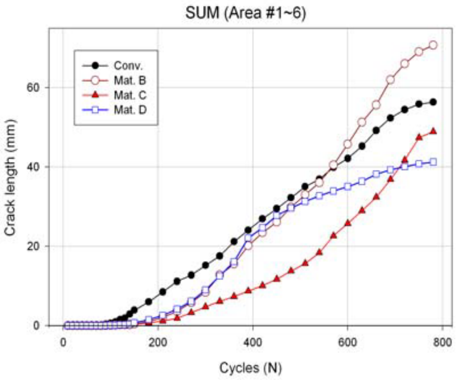
(a) Observation spot 1 (b) Observation pot 2 (c) Observation spot 3

Fig. 7. Cracks in material C after 780 thermal cycles



(a) Observation spot 1 (b) Observation pot 2 (c) Observation spot 3

Fig. 8. Cracks in material D after 780 thermal cycles



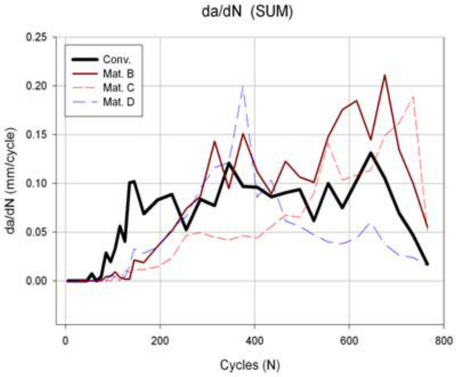


Fig. 9. Total crack length vs. thermal cycles

Fig. 10. Crack propagation rate vs. thermal cycles

4. Conclusion

We performed thermal shock fatigue tests for three candidate cast iron and a specimen made from a disc in service use. The temperature range for the thermal fatigue was 25□~600□.

1) The thermal fatigue test process developed in this study is very effective.
2) Mechanical properties can be easily controlled by varying Ni, Co and Mo contents.
3) The three candidate castings have compact vermicular graphite and higher resistance to thermal cracks than the disc material in use which has flake graphite. Material C has the highest thermal resistance.
4) Several dominant thermal cracks propagate and are combined.
5) The conventional material Conv. has a shorter crack initiation life.

Acknowledgements

This study was supported by the Korea Research Council for Industrial Science affiliated with the Ministry of Knowledge Economy. We are grateful for the support.

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