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Measuring of Core Split Line Defect on Pillar Type Vented Brake Disc and Investigation of Crack Occurrence Potential on the Disc Caused by Its Geometric Deviation

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Abstract

In this study, a measuring method was defined to convert the level of defects on the pillar type vented brake disc to numeric data where the defects were formed due to missing material in the structure of the disc. Subsequently, the geometric defects which are existing in the core on the droplets were examined with the defined method in only pillar type vented brake disc. Finally, some thermal performance tests (brake disc thermal fatigue test on bench in accordance with Society of Automotive Engineers Brake Rotor Thermal Cracking Procedure for Vehicles (SAE J2928) [1] and brake disc crack test on vehicle; special test procedure of an original equipment manufacturer, which is performed for inspecting structural strength) and thermal fatigue test with thermal shock (test procedure formed by authors) were performed with defected brake discs to evaluate the risk of defected brake disc usage on the vehicle in terms of safety. The main open point is to determine whether the defect can transform to crack by influencing with notch effect during the worst usage conditions. In the conducted tests; it was investigated that the worst core split line defects which are specified by the defined measuring flow may cause a crack formation by proceeding notch effect under the worst usage condition. In order to simulate the worst usage condition; test laboratories, equipment and test track were used in this period for performing brake disc thermal fatigue test, crack test with thermal shock and crack test on vehicle.

Keywords: Brake disc, casting defect, core, crack analysis, thermal fatigue

1. Introduction

In conventional vented brake discs, different types of ventilation geometries such as pillar, straight or curved are used in order to achieve expected thermal performance on the vehicle. To provide homogeneous heat dissipation, the pillar type vents are generally preferred by original equipment manufacturers. T.J. Mackin et.al. studied that brake rotors are subjected to high thermal stresses during routine braking conditions and can reach temperatures as high as 900 °C during hard braking. These thermal stresses reduce fatigue life of the brake rotor by developing macroscopic cracks on the rotor. These large temperature excursions have two possible outcomes: thermal shock that generates surface cracks; and/or large amounts of plastic deformation in the brake rotor [2, 3]. To create the ventilation geometry, sand core is used into the casting molds and the final pillar geometry is always negative of the sand core geometry [3]. Therefore, if there is a geometric deviation on the core surface, its negative form of the deviation would be observed on the opposite side after casting. It means that, if 1 mm burr is existing on the core split line, this defect will appear on the casting part as 1 mm missing material. This defect, which has not a specific geometry and dimension, is defined in literature as "joint burr" or "core trace" when caused excess material on split line [4]. Core split line defect can be cleaned by grinding when it is formed as excess material, but no corrective actions can be made when it forms as a missing material. In case of 1 mm defect existence on the core split line after casting operation, it is possible that total interface area reduction of the pillar halves is about 18% in average. It means that, the strength of the pillar, where stated into the disc, decreases if the defect level increases on the core split line of the part [5]. Therefore, this common irregularity is considered as an important risk factor, since brake disc is a security part. Nowadays, the sand cores are designed uniquely according to ventilation geometry of the disc and printed generally by cold box method [6, 7, 8, 9]. After the cores are pressed in core box, some split line burrs remain on the cores and normally these burrs must be cleaned by a cleaning equipment to provide the designed disc geometry. But some burrs might remain on the split line and cause a geometric irregularity onto the pillars. In addition to this, it causes missing material like a trace through the whole split line. This defect can be defined as “core split line irregularity”.

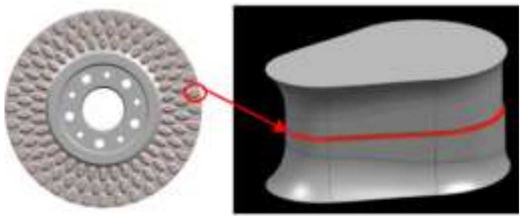

Figure 1. Core split line irregularity illustration on the brake disc pillar.

The defect illustration is shown Figure 1. This type of geometric defect can cause micro or macro cracking on the disc pillars during braking under high temperature and pressure [10, 11]. Goo et.al. investigated the thermal fatigue characteristics of cast iron brake disc under high load pressure. The mechanical and thermal properties of the samples were measured. Thermal fatigue tests were then carried out using equipment developed by the author. It is claimed that the fatigue lifetime of cast iron could be increased by regulating its composition and metallurgical structures [12, 13]. In another study, Gigan et.al. investigated thermo mechanical fatigue of grey cast iron brake discs for heavy vehicles via finite elements method. They claimed that the analysis of stress-strain hysteresis loops showed that the mechanical properties drop substantially at high temperature (above 500 °C) [14, 15]. Maraveas et. al. studied mechanical properties of structural cast iron at elevated temperatures up to 900 ^{0}C and after cooling down by quenching and air flowing. Their study claims that cast-iron structures can be restored after fire damage, provided there is no visible damage [16, 17]. Brake is the most indispensable safety measure of a vehicle which is quite significant in this context where unexpected noise and vibration from the brake provide information about its status, being faulty or not. Such noise and vibration problems are encountered mainly in highway, railway, airway and off-road vehicles, large-scale work machines, oil drilling rigs and mine lifting systems [18] Due to related studies in literature and feedbacks from manufacturers, noise and accompanying vibration mostly occur as a result of the material of the intermediate parts in the brake, wear over time, or the dimensional errors in the design stage[19].

2. Defect Detection and Measuring Method

Detection and measurement processes of the defect were done according to the flow shown in the Figure 2-3, considering the mold mismatch. One of the important criteria is to consider the saw thickness which was used to cut the disc for defect detection. The thickness of the saw should not be thicker than 2 mm to provide the measurement accuracy. Thicker saws can cause material loss on the defect area.

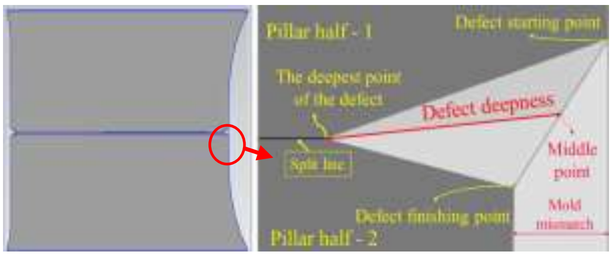

Figure 2. Measuring method of the core split line irregularity under microscope.

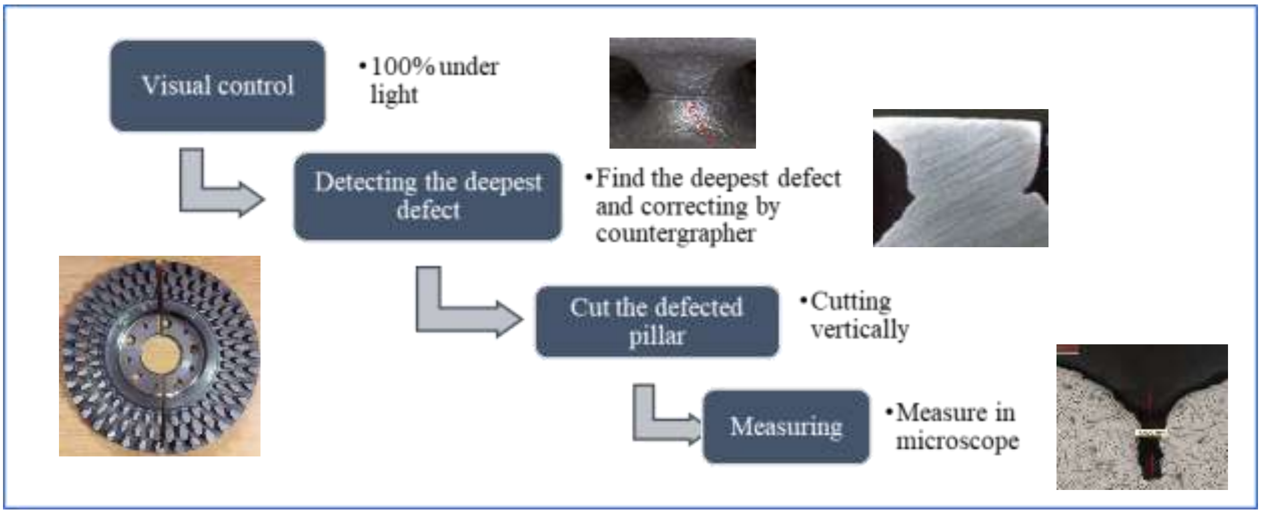

Figure 3. Measuring systematic of the core split line irregularity

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2. Defect Detection and Measuring Method

Before testing, 4 different types of vented brake disc were examined with above specified method in terms of 10 samples which were selected from each type of those brake discs were measured by contour measuring [20] and reported in Figure 4. According to analysis results, the defect characterizations were similar in Type 1 and Type 3. But standard deviation of the defects was bigger in Type 1 (See Figure 5). Also, it is seen that the depth of defects in Type 1 were distributed in a larger range compared to other types. (see Figure 6). After evaluation of the outputs, it was decided to carry out the tests with Type 1.

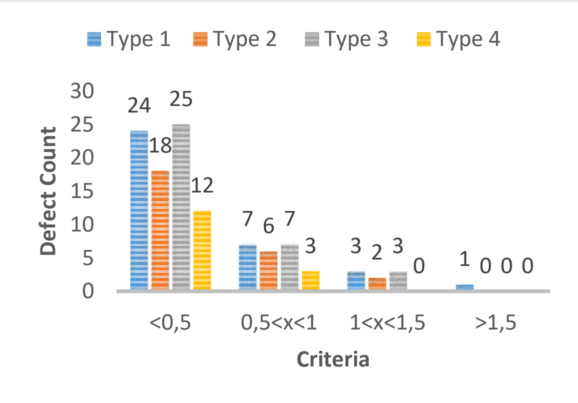

Figure 4. Detected defect amount in inspected 4 type vented brake discs.

The defect depth for each defect was measured non-destructively by contour measuring. The worst discs which had the defect deepness over 1 mm were selected to perform destructive tests. After the tests, samples from these discs were cut and the defects were measured destructively under microscope according to the defined measuring method. In the meantime, occurrence of any crack on the pillars by notch effect was analyzed under microscope.

Table 1. Some characteristics of inspected disc types.

Brake disc	Type 1	Type 2	Type 3	Type 4
Ventilation gap (core thickness) (mm)	10	8	8	12
Pillar Count	108	90	90	93
Total interface area in narrowest section (mm^2)	9270	10753	10753	9970
Casting Method (Moulding)	Vertical	Vertical	Vertical	Horizontal
Core Making Method	Cold box, Painted with water-based paint	Cold box, Painted with water-based paint	Cold box, Painted with water-based paint	Cold box, Painted with water-based paint

defect profile. Each type of brake discs was produced by different foundry. Some defect examples are shown in Figure 7 and comparison table is presented on Table 1.

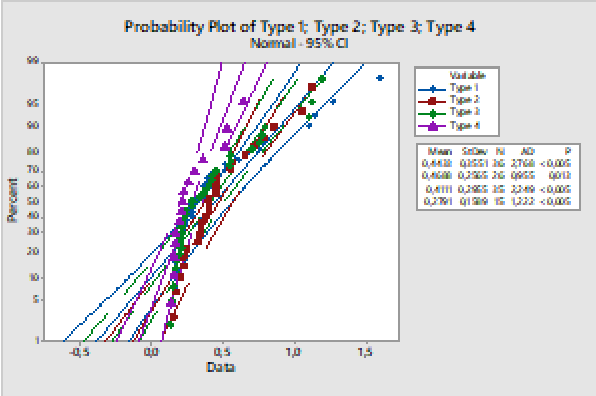

Figure 5. Defect distribution and standard deviation for 4 types.

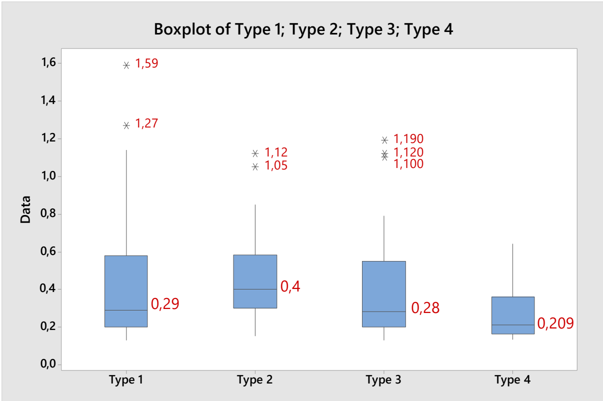

Figure 6. Distribution of the defect for each brake disc type.

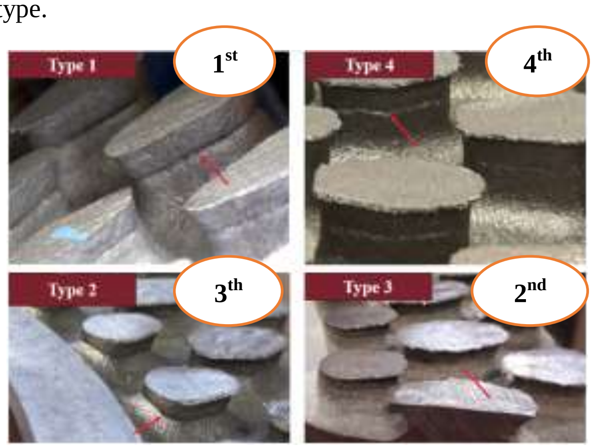

Figure 7. Defect sample on the pillars in 4 types vented discs.

2.2. Tests

All tests were carried out in a test facility which is approved by an engineering department of an OEM.

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2.2.1. Crack Test (brake disc thermal fatigue test)

The crack test is a structural validation test and generally it is performed according to the regarding standard during the development, design change or material composition change of a part in brake system. The purpose of the test is to assess the capacity of the disc to resist initiation and propagation of cracks on the braking surface and pillars resulting from repeated exposure to thermal stress. Test setup is presented in Figure 8.

Figure 8. Crack test on bench, mounted rotor on dyno.

The brake disc is mounted to the bench together with the components (friction material, caliper, knuckle, hub, bearings) to which it is connected, except the wheel. The rotor speed is increased to 80 km/h then it is decreased to 0 km/h gradually. During this cycle, brake applications are repeated for 100 times after bedding. The same cycle is carried out at least three times and the crack occurrence are investigated on the disc.

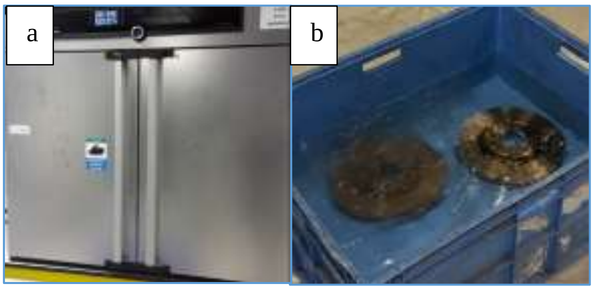

Figure 9. Thermal shocked crack test equipment. **a.** etuv, **b.** water pool.

2.2.2 Thermal Shocked Crack Test

This test is carried out by heating up the disc to 300 ^{0}C, holding it at least 30 minutes in the furnace and then sinking it suddenly to a water pool in room temperature according to regarded standard (see Figure 9 for test equipment). After the rotor and water temperatures are equal, crack formation is investigated on the disc.

2.2.3. Thermal Shocked Crack Test on Vehicle

This test is conducted for simulating the customer usage in the worst environmental conditions. The test is carried out in the performance route by using a pool filled with water which has 10 m length and 30 cm height. The temperature of the water should be between 20-25 ^{0}C. A thermocouple is mounted into the pads for measuring the brake disc temperature during the test. The rotors, which are inspected to have defect levels above 1 mm, are mounted to the vehicle. After the disc surface temperature is increased over 300 ^{0}C, the vehicle is driven in the pool 3 times with 30 km/h in series according to regarded standard. Afterwards, the rotors are dismounted from the vehicle and crack occurrence is investigated on the pillars. Assembled brake disc on vehicle is presented at Figure 10.

Figure 10. Assembled brake disc on vehicle after thermal shocked crack test on vehicle.

3. Results and Discussions

3.1. Crack Test on Bench & Results

Four rotors that have visually higher defect depth out of 30 rotors which have core split line defect were tested to analyze their crack occurrence. Maximum defect depth and occurrence of cracks on defects' base upon rotors, which cut with fret saw, were analyzed via defined methodology after crack test (Figures 11, 12a, 12b, 13a and 10b) and the results are shown on Table 2.

Table 2. Depth values of core split line after crack test.

Test 1	Def. 1	Def. 2	Def. 3	Def. 4	Def. 5	Def. 6
Rotor 1	0,8	1,11	1,16	1,1	1,2	0,9
Rotor 2	0,75	0,9	1,12	1,59	0,1	0,94
Rotor 3	1,1	0,8	1,15	0,96	0,9	0,85
Rotor 4	1,2	0,7	1,25	0,55	0,9	0,88

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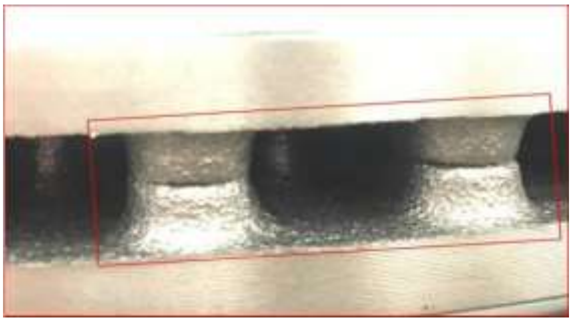

Figure 11. Selected brake disc for the test.

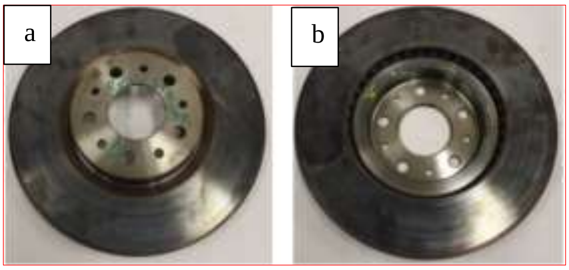

Figure 12. Rotors after crack tests. **a.** left, **b.** right.

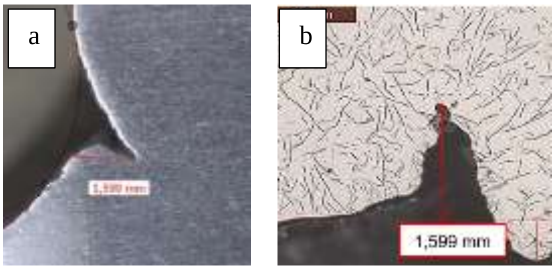

Figure 13. Defect analysis under microscope after crack test. **a.** measurement, **b.** crack analysis.

Before crack test on bench, bedding (burnishing) was implemented for simulating customer usage more realistic results.

3.2. Crack Test with Thermal Shock Results

Defect areas on 4 rotors were analyzed after test (Figure 14, 15a, b, c, d, e). Depth of defects are shown on Table 3. Crack occurrence of 4 pillars that has highest depth was investigated.

Figure 14. Rotors after crack test with thermal shock.

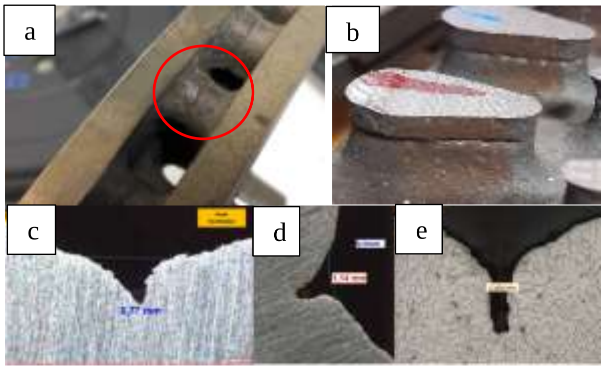

Figure 15. Defects after crack test with thermal shock. **a.** and **b.** defect view, **c, d,** and **e** defect analysis.

Table 3. After thermal shocked crack test, measured maximum defect depths.

Test 2	Def. 1	Def. 2	Def. 3	Def. 4	Def. 5	Def. 6
Rotor 1	0,77	1,1	0,95	0,82	1,14	0,65
Rotor 2	1	0,67	1,12	0,95	0,85	0,88
Rotor 3	0,55	0,94	0,54	1,16	0,65	0,77
Rotor 4	0,85	0,55	1,15	1,1	0,95	0,8

3.3. Results of Thermal Shocked Crack Test on Vehicle

In this test, 2 rotors which were specified as worst according to defined measuring method, were mounted and tested on vehicle. After test, the core split line defects were measured and analyzed crack occurrence under microscope (Figure 16a, b, c). The results are shown in Table 4.

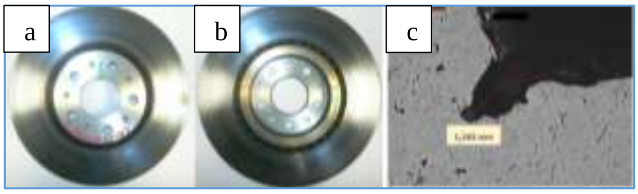

Figure 16. The tested rotors, **a.** left wheel, **b.** right wheel and **c.** analyzing under microscope.

Table 4. The Defect Depths After Test.

Test 3	Def. 1	Def. 2	Def. 3	Def. 4	Def. 5	Def. 6
Rotor 1 (Right)	1,17	0,77	0,9	0,65	1,12	1,14
Rotor 2 (Left)	1,05	0,6	0,85	0,96	1,24	1,18

4. Conclusion

The effect of worst-case core burrs on rotor pillars which has potential risk of crack occurrence on rotor surface was investigated via measurements on depth of those defects which has no regular geometry and dispersion.

- Core burrs with deviation on geometric forms were observed on rotors which were 4 different type of pillar geometry on each. It was also observed that those rotors have 15% of split line defect on their pillars.
- A new methodology was defined to classify the trace on core dimensionally. It is understood that the level of the core split line defect can be determined by contour measuring equipment without any destructive operation.
- Approximately 20% of defects was measured with more than 1 mm depth within all depth distribution. The maximum defect depth was 1,6 mm.
- No cracks on surface of rotors and pillars were observed after crack test (1st test) on bench test. There was any micro crack via checking under microscope. The maximum defect depth was 1,6 mm.
- No cracks – even micro cracks – were observed after thermal shocked crack test (2nd test) on laboratory. The maximum defect depth was 1,16 mm.
- No crack or breakage on pillars were observed after thermal shocked crack test (3rd test) on vehicle. The maximum defect depth was 1,24 mm. Besides, there was no micro-crack on the base of defect.
- It could be evaluated that there is no safety risk (crack and/or breakage) for the Type 1 ventilated rotors which have less than 1.6 mm defect.

This work does not constitute a reference for listed situations below;

- ➢ Rotor has min. 15% of its pillars has that kind of defect,
- ➢ Rotor which min. 20% of its pillars has more than 1 mm defect
- ➢ Brake rotors which have core split line defect on pillars with deeper than 1,6 mm defect.

To verify exact behavior of brake rotors under these circumstances, it is needed to perform a further study based on a proper design of experiment.

Author's Contributions

Recep Akyüz: Drafted and wrote the manuscript, performed the experiment and result analysis.

Eren Kulalı, Ramadan Soncu, Cem Öztürk, Mehmet Karaca: Assisted in analytical analysis on the structure, supervised the experiment's progress, result interpretation and helped in manuscript preparation.

Ethics

There are no ethical issues after the publication of this manuscript.

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