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Improvement of railway brake discs using new cast iron materials

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PhD dissertation thesis booklet

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Theses

The aim of this work is to develop further the brake discs of railway vehicles, taking into account the characteristics of the new cast iron varieties. I present and evaluate the state of the art of road and rail vehicle brake discs [18], [12]. For many years, similar technologies and materials have been used in rail vehicle brake discs. New developments and achievements in other applications have emerged among the automotive brake discs, but they have never, exceptionally, ever been used in railway vehicles [1], [9], [10], [20].

I have examined the existing rail brake disc materials, the thermomechanical properties of the steel materials and the new cast iron, in particular the temperature conductivity factor (α_t), the specific heat capacity (c_p), the thermal conductivity factor (λ), the thermal expansion factor (α_i), yield strength ($R_{p0.2}$) and tensile strength (R_m).

Thesis 1:

By analyzing measurement results of industrial research [15], [16], [20], I have stated that the new high carbon cast materials in case of brake discs application are more favorable in terms of the temperature conductivity coefficient α_t and in case of the thermal conductivity coefficient λ than conventional cast iron or forged steel used in brake disks.

Within an accuracy of ± 5%

a) the thermal conductivity coefficient λ increases by an average of 8% and the temperature conductivity coefficient α_t by an average of 10% compared to hitherto used cast iron
b) the thermal conductivity coefficient λ increases by an average of 45% and the temperature conductivity coefficient α_t increases by a mean value of 50% compared to hitherto used forged steel

(detailed in Chapter 6.1 of the dissertation)

Thesis 2:

By analyzing measurement results of industrial research [15], [16], [20], I have stated that then yield strength $R_{p0,2}$ and the tensile strength R_m of new high-carbon cast iron are lower than the values of conventional cast iron or forged steel used in brake disks.

Within an accuracy of ± 5%

a) compared to cast iron used hitherto in brake disc applications the yield strength $R_{p0,2}$ and the tensile strength R_m are reduced by an average of 30%.

(b) compared to forged steel used hitherto in brake disc applications the yield strength $R_{p0,2}$ and the tensile strength R_m are reduced by an average of 80%.

(detailed in Chapter 6.1)

Thesis 3:

By analyzing the results of finite element calculations [55], [s5], [s7] I proved, that due to the favorable design of the connection from friction ring to the wheel or axle, what is possible by using of the cast iron material, the thermomechanical stresses can be reduced by more than 30% during the braking process. (detailed in chapter 7.5 of the dissertation)

Thesis 4:

I have proved by finite element calculations [8], [s6], [s1] that the average temperature of the brake disc friction surface can be reduced by more than 65°C using materials with high thermal conductivity according to my calculations, when braking at a top speed of 320km/h. This temperature reduction allows a wide range of UIC standard brake pads to be used. (detailed in chapter 7.4 of the dissertation)

Background, justification and purpose of the research

One of the main systems of a railway vehicle is the braking system. According to current practice, the basis material of brake discs is cast iron [12]. In special circumstances, such as the need for high speed or low axle load, brake discs are made of steel or aluminum [1], [18], [6]. However, essentially no material is optimized for this application. Aluminum is not suitable because of its behavior in case of failure. And steel is not perfect because its thermal conductivity and heat capacity are very low, so special brake pads are needed.

In the last twenty years, automotive engine and brake disc innovations have resulted in new cast iron varieties. For example, one such cast iron contains vermicular graphite instead of lamellar graphite [10] and another has an elevated carbon content ratio [9], [11].

After extensive literature research in the field of brake disc shapes and material properties, general analytical calculations are performed. As a result of the calculations, the dependence of the thickness and weight of the brake disc friction ring on the friction and wear properties of each alternative material is determined. This is followed by a FEM computational calculation, which covers brake disc deformation and low disc fatigue test.

A other purpose of this dissertation is to investigate the appropriate technologies for connecting selected brake disc systems to rotating parts.

Methodology

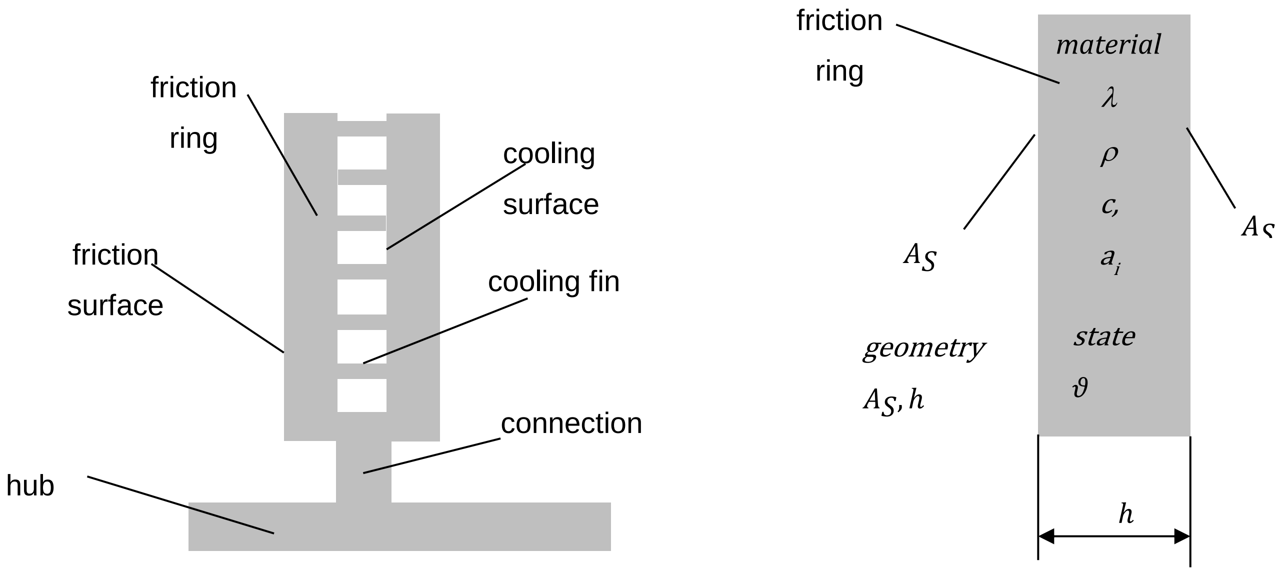

figure 1 1: ***Brake disc lower part: Properties of the friction ring***

In order to find usable solutions, the original infinite solution space is regarded. In this study, the solution space can be reduced to available solutions due to limited unit costs. The characteristics of the rail vehicle brake, which are defined by the used control system, are functionally analyzed.

The solution space can be divided into separate scopes. On the one hand, friction discs are a set of solutions that include brake discs and internal combustion engine materials, that have been introduced over the past eight years. The second set of solutions involves connecting the friction disk to the rotating parts. Here again, we focus on solutions that have been introduced or patented over the past eight years.

The potentials of the selected technologies can be estimated based on the reference mass of the brake disc. A minor factor is the cost of production. For the purposes of this investigation, it is sufficient to determine the costs simply by estimating the necessary production steps. The comparison was made with the GJL 250 a friction material and conventional axially split brake disk as reference value.

Theses 1

The new high-carbon cast iron materials have more favorable properties in terms of thermal conductivity and temperature conductivity, than conventional gray cast iron or forged steel disc material.

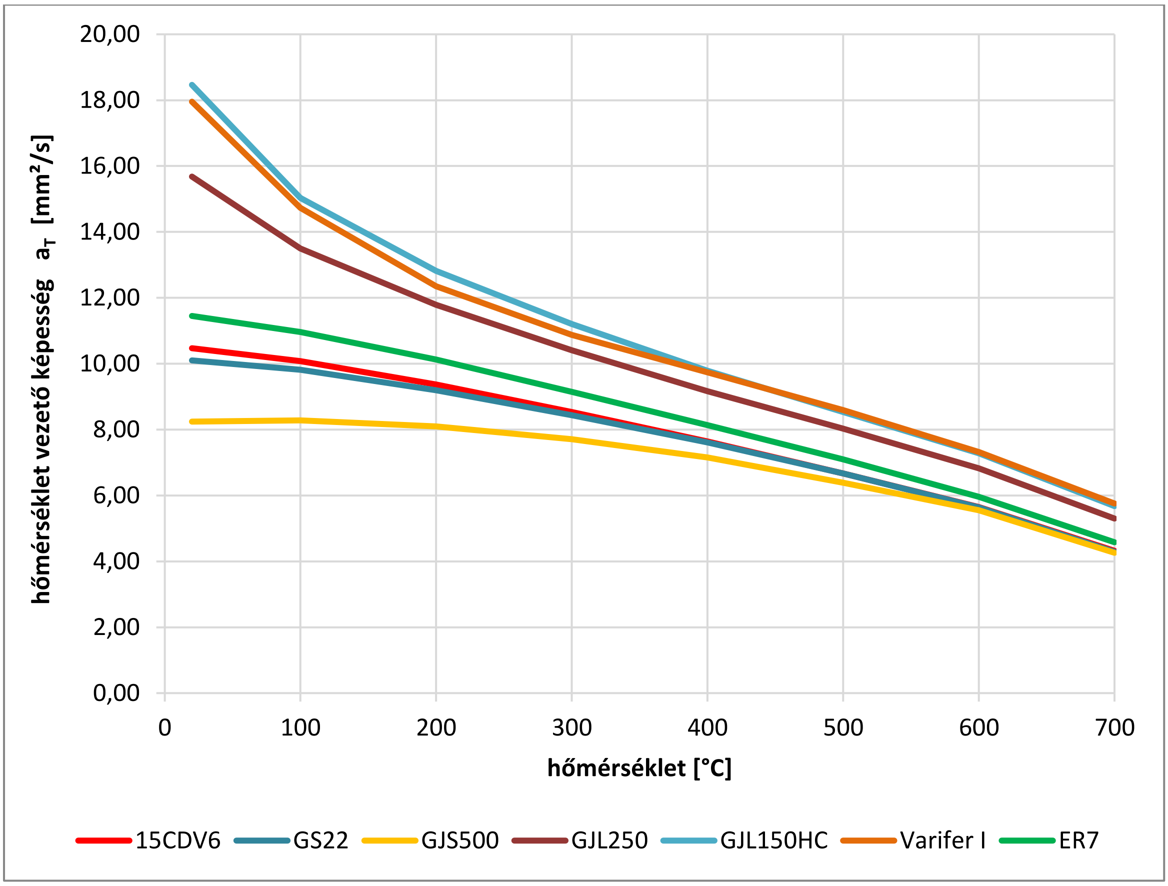

figure 2: the temperature conductivity coefficient α_t [15],[20]

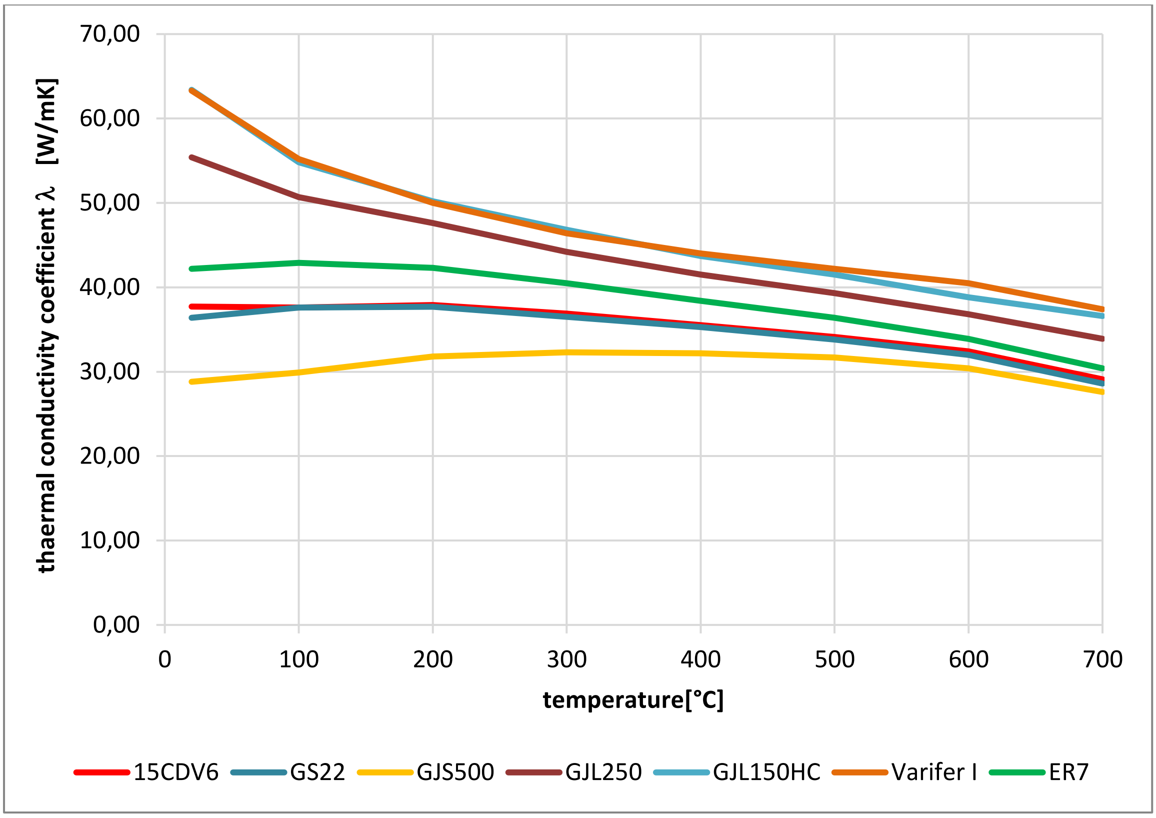

figure 3: the thermal conductivity coefficient - λ [15],[20]

Temperature conductivity decreases with increasing temperature, in the temperature range of all test materials. The three groups of materials exhibit distinct differences in behavior between flat-cast iron, ductile iron and steel. At low temperatures, the temperature conductivity of cast iron grades is greater than 1.5 than the temperature conductivity of steels. At higher temperatures the differences are reduced but still significant.

The specific heat capacity increases strictly in a monotonous fashion as the temperature increases, almost doubling between 20 ° C and 700 ° C. Flat graphite cast iron has a specific heat capacity of approximately 5%. The difference between the three groups of materials, namely graphite cast iron, spheroidal iron and steel, is not very meaningful.

anyag	forrás	fajlagos hőkapacitás	hővezetési tényező	sűrűségű	hőmérséklet vezetési tényező
		c	λ	ρ	a_T
		J/kgK	W/mK	kg/m³	mm²/s
15CDV6	[53]	480	37,6	7814	10,02
GS22	[53]	490	37,6	7801	9,84
GJS500	[53]	510	29,9	7124	8,23
GJL250	[53]	520	50,7	7214	13,52
GJL150HC	[68]	510	54,8	7135	15,06
Varifer I	[68]	520	55,2	7176	14,79
ER7	[53]	500	42,9	7836	10,95
15CDV6 vs. GJL150HC		0,98	1,08	0,99	1,11
GJL500 vs. GJL150HC		1,06	1,46	0,91	1,50

table1: the thermical properties at 100°C

The cast iron materials GJL150HC, GJL250 és Varifer got the best results.

Thesis 2

The new high carbon cast iron has properties that are less favorable in terms of yield strength and tensile strength than conventional cast iron or forged steel.

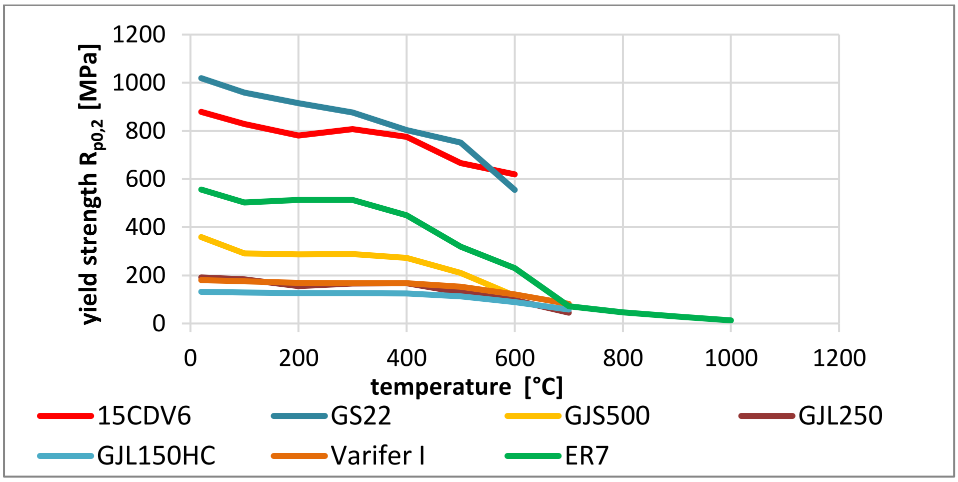

Figure 4: the yield strengh- $R_{p0,2}$ [15],[20]

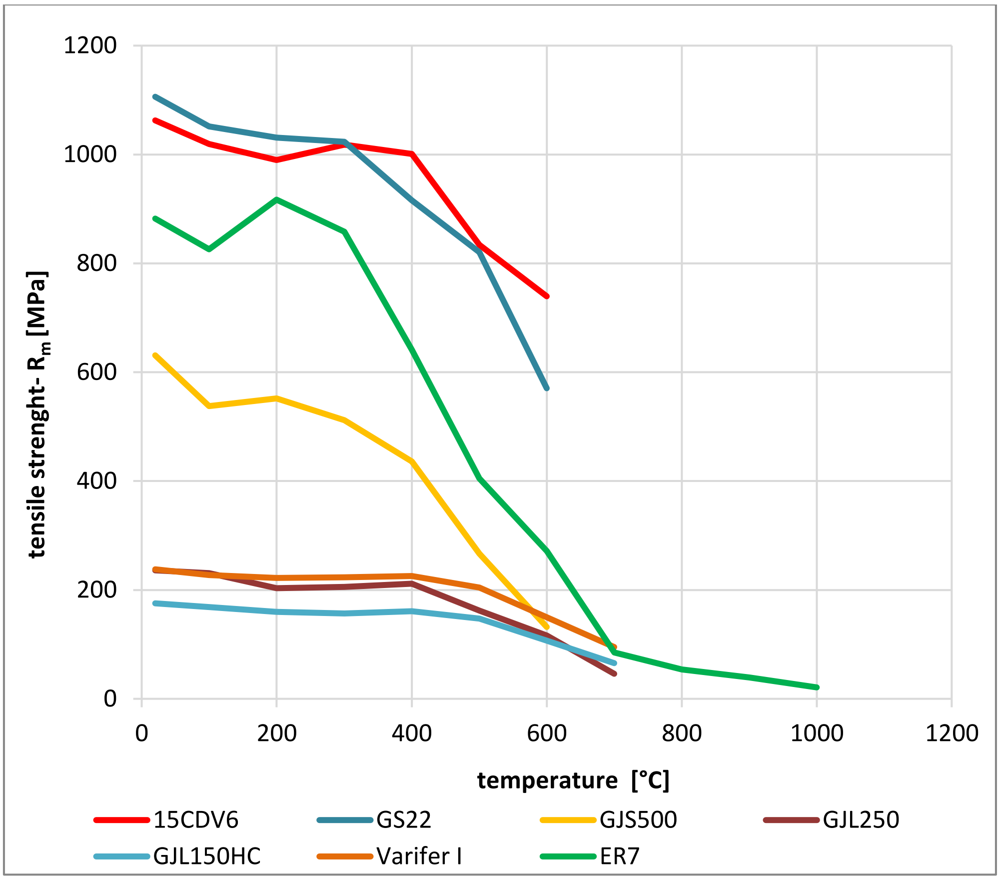

figure 4: the tensile strength - R_m [15],[20]

The yield strength, as a primary strength value, is as follows. The strength of steels is many times (3-6 times) higher than that of cast iron. It is worth noting that the yield strengths of 15CDV6 and ER7 increase slightly over the temperature range up to about 300 ° C. The difference decreases slightly with temperature, but essentially remains. However, Varifer achieves strength values similar to the values of the GJL250 material that are is significantly higher than GJL150HC. This can be especially important, when casted fins are used to connect the friction ring to the hub to transfer accelerated weight and braking torques.

The tensile strength as a secondary strength value behaves as follows. The strength of steels is often (3-6 times) higher than that of cast iron. It is worth noting that the tensile strength of 15CDV6 and ER7 increases slightly over the temperature range up to about 300 ° C. The difference decreases slightly with temperature, but essentially remains. Again, Varifer achieves strength values similar to the values of the GJL250 material, that are significantly higher than the GJL150HC.

anyag	forrás	folyás-határ	szakító-szilárdság	rugalmassági modulusz	Poisson tényező	hőtágulási tényező
		$R_{P,0,2}$	R_m	E	ν	a_i
		N/mm²	N/mm²	N/mm²		1/K
15CDV6	[53]	829	1019	205000	0,30	1,18E-05
GS22	[53]	959	1051	199500	0,30	1,24E-05
GJS500	[53]	291	538	168000	0,26	1,15E-05
GJL250	[53]	183	231	102000	0,26	1,09E-05
GJL150HC	[68]	129	168	108300	0,26	1,10E-05
Varifer I	[68]	175	227	122000	0,26	1,13E-05
ER7	[53]	556	826	202000	0,30	1,14E-05
15CDV6 vs. GJL150HC		0,70	0,73	1,06	1,00	1,01
GJL500 vs. GJL150HC		0,16	0,16	0,53	0,87	0,94

table 2: the mechanical properties at 100°C

The steels 15CDV6, GS22 és ER7 got the best results

Thesis 3

As a result of the favorable design of the brake disc connection to the wheel or axle, the thermomechanical stresses can be reduced by more than 30% during the braking process

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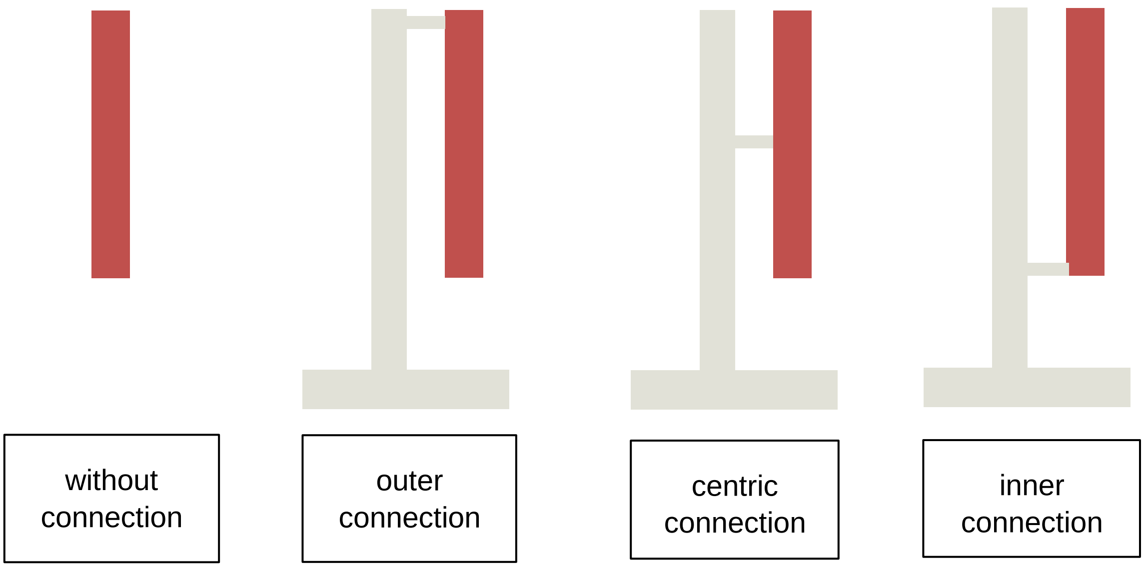


figure 5: the investigated geometric variants

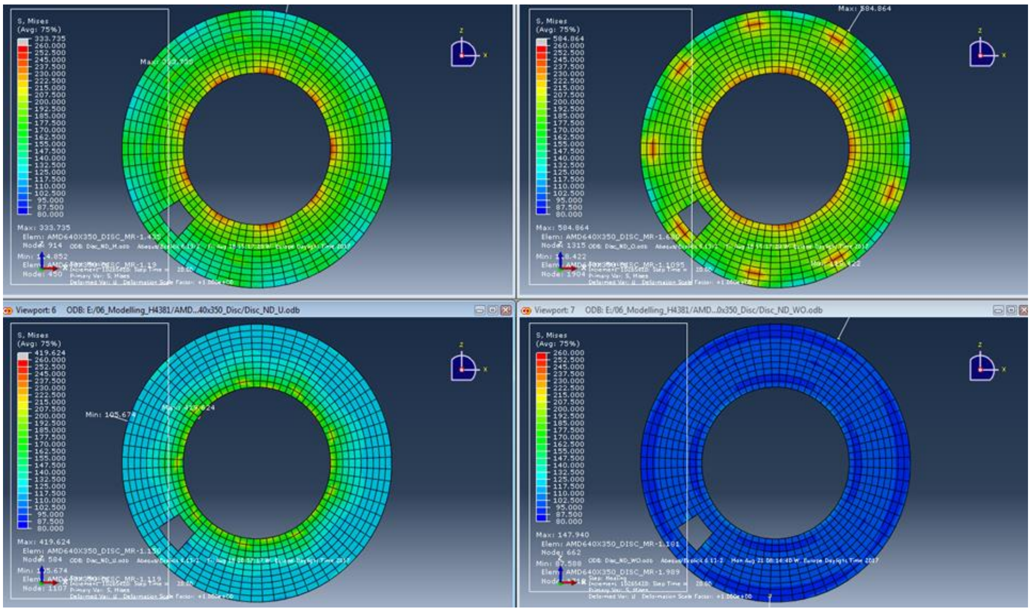


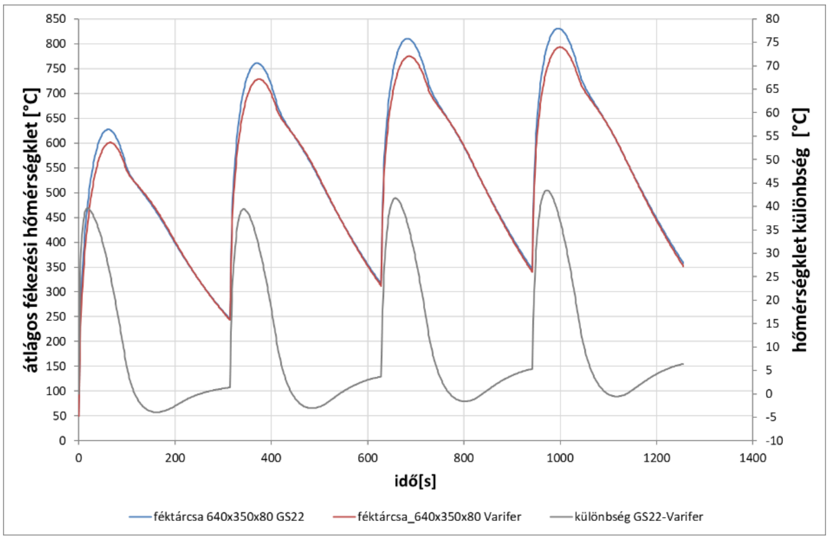
figure 7: the v. Mises stresses at the friction surface [17]

Stresses on the friction surface remain low in the brake disc without the ribs being directly attached to the surface. Hotpots appear on the friction surfaces at the joints, although the joints are on the cooling surface. In addition, the stress level is globally higher for all three connection types than for friction less surfaces with the not possible example with no connection. Inner radius is particularly critical. The outer attachment point prevents the entire friction ring from moving freely, and the hotspots reappear in the area inward from the outer attachment point.

The attachment points also have a global effect, even if the brake disc is located away from the attachment point, the stresses increases significantly (see, in particular, the image with the attachment at the outer edge of the friction ring).

Theses 4

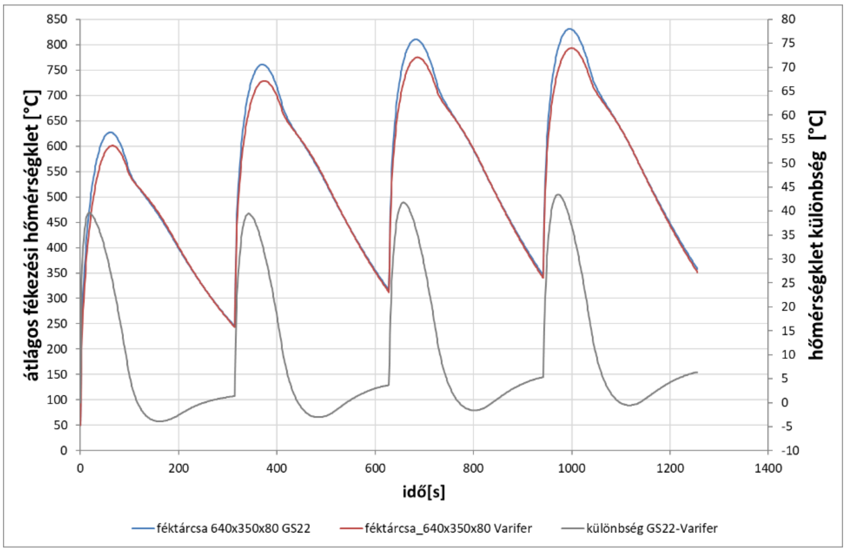
By using materials with high thermal conductivity, the friction surface temperature can be reduced by more than 65 ° C during braking at a maximum speed of 320km / h.



magas energia fékezés - WBS 640x350x80 GS22 vs. Varifer

- Maximum átlagos hőmérséklet GS22: 831 ° C
- Maximum átlagos hőmérséklet Varifer: 793 ° C
- Maximum hőmérséklet különbség: 43 ° C

figure *8*: the temperature / speed time diagram at braking from high speeds - [8]



magas energia fékezés - 640x350x80 GJL vs. Varifer

- Maximum átlagos hőmérséklet GJL250: 784 ° C
- Maximum átlagos hőmérséklet Varifer: 767 ° C
- Maximum hőmérségklet különbség: 18 ° C

figure 6: the temperature/ speed time diagram at braking from high speeds - [8]

Using cast iron, the geometry of the finds and connections can be easily matched to enlarged surfaces with better cooling. This again leads to a reduction in the friction surface.

Combining material change and rib geometry modification, the maximum brake disc temperature can be reduced from 831° C to 767°C, or by 65°C.

During the first braking, the maximum temperature of the brake disc can be reduced from 625 °C to 575°C, ie a cooling of 50°C is achieved. Below the 600° C limit, it is maybe possible to use conventional brake pads.

Summary, directions for further development, practical application possibilities

Summary

The new high-carbon cast iron offers better performance in terms of both, heat conductivity and heat capacity than sheet graphite, chromium molybdenum vanadium alloy forged steel and conventional cast iron. Temperature conductivity is critical for brake discs. Compared to conventional cast iron he thermal conductivity factor λ increases by about 8%, and the$_t$ temperature conductivity factor increases by approximately 11%. Compared to conventional forged steel, the thermal conductivity increases by about 45% and the temperature conductivity increases by about 50%.Thanks to the favorable design of the connection between the brake disc and the shaft, the thermal stresses during braking can be reduced by 31%. Using materials with a high thermal conductivity factor λ, the temperature of the friction surface heated at high speed v can be reduced by more than 65 ° C.

This allows a wide range of UIC-shaped brake pads to be used in some applications

Practical application possibilities

Cast iron materials have a clear potential for the use as brake discs for rail vehicles. The first tests show that they effectively reduce the temperature of frictional contact during the braking process and the stresses and strains on the brake disc. However, for practical application, it is important to develop new types of brake discs that take advantage of the beneficial properties of these materials. In addition to the friction surface properties, the material properties can also be used for cooling system and connection optimization. To use the advantage of the material with higher thermal conductivity coefficient, a cooling system has to be designed, what uses in addition the better formability, what allows the radiator fins to be freely selected for better heat dissipation.

Directions for Improvement

As a follow-up, three areas of research are:

- Brake Pads - Brake Disc interaction, using new cast iron materials from a thermomechanical and mechanical point of view. (deformation, heat distribution)
- Optimal connection and stiffness for new cast iron materials
- Optimal cooling system for high speed trains, using new cast iron materials. (heat sink shape)

Publications of the author

[s1]**Weber, F.J.:**

MultiPhysicsSimulation zur Lösung der Zielkonflikte bei der Entwicklung klotzgebremster Eisenbahnräder.

6. Grazer Symposium Virtuelles Fahrzeug, Graz, 2013

[s2]**Strommer, K. / Weber, F.J.:**

The ADI spoke wheel-new developments to meet new requirements

9, International Wheelset Congress, 16.-20. April 2019, Venice

[s3]**De la Prida, R. / Weber, F.J.:**

Developement and Homologation of a Monobloc Wheel according EN 13979 / UIC 510-5. Case Analysis of Cargo Alpine ®

First European Forum on Railway Running Gears – June 2011 – Leganés. Madrid. Spain

[s4]**Kleinschuster, C. / Weber, F.J.:**

Heat Transfer in Railway Brake Disks - a critical review

Proceedings of the Institution of Mechanical Engineers, Part F, Journal of Rail and Rapid Transit (tervezett)

[s5]**Raninger, P./ Ecker, W./ Marsoner, S./ Schinagl, G./ Weber, F.J.**

Modeling of the in-service behavior of brake disks for railway applications, Thermophysical data and low cycle fatigue behaviour, Int. J. Fatigue (tervezett)

[s6]**Stine, G. / Weber, F.J. / Zenz, R.:**

Hochleistungsbremsscheiben und Hochleistungsräder für Hochgeschwindigkeitszüge

ZEVrail Glasers Annalen 146 (tervezett)

[s7]**Weber, F.J., Zenz,R.;**

RAIL WHEEL WITH WHEEL-MOUNTED BRAKE DISK

AT514902 (A1) — 2015-04-15

Publications

[1] **Alsaif, M. A. / Dahm, K. L. / Shrestha, S. / Dearnley, P. A. / Barton, D. C.:** Plasma Electrolytic Oxidation (PEO) treated aluminium metal matrix composite rotors for lightweight automotive brakes. In: 6th European Conference on Braking, Lille, Frankreich, 24./25. November 2010

[2] **Bertodo, R.:** Grey cast irons for thermal-stress applications Journal of Strain Analysis, Volume: 5 issue: 2, page(s): 98-109 April 1, 1970

[3] **Blau, P. J. / Jolly, B. C. / Qu, J. / Peter, W. H. / Blue, C. A.:** Tribological investigation of titanium-based materials for brakes. In: Wear 263 (2007), S. 1202–1211, 2007

[4] **Cueva, G. / Sinatora, A. / Guesser, W. L. / Tschiptschin, A. P.:** Wear resistance of castirons used in brake disc rotors. In: Wear 255 (2003), S. 1256–1260, 2003

[5] **Füllgrabe, F.:** Neue Konzepte für Leichtbau-Bremsscheiben auf Basis metallischer Werkstoffe, Dissertation TU Darmstadt, 2012

[6] **Kevorkijan, V. M. / Dragojevič, V. / Smolar, T. / Lenarčič, D.:** A brake disc in Al-based composite. In: Materiali in Tehnologije 36 (2002), 2002

[7] **Kleiner, S., und Track, K..:** SiMo1000 – Ein aluminium-legiertes Gusseisen für Hochtemperaturanwendungen Giesserei 97 (2005)

[8] **Kleinschuster, C**.: Wellenbremsscheibe Performancevergleich, Siemens RS BG EN SDE BRA, Graz, 2018, (kiadatlan)

[9] **Keiner, W. , Werning, H.:**Hochgekohlter Grauguss GG-15HC—Idealer Werkstoff für Bremsscheiben und Bremstrommeln, Konstruieren Giessen 15 (4) (1990)

[10] **Lampic, M., Walz, M.:** Innovative Eisengusswerkstoffe für Automobilteile - Six Sigma“ konform. konstruieren + giessen 30 (2005) H. 4, S. 16 - 22.

[11] **Langmayr, F., Zieher, F. & Lampic, M.** Thermomechanik von Gusseisen für Zylinderköpfe MTZ Motortech Z (2004) 65: 298.

[12] **Le Gigan, G.; Lundén R.; Vernersson T.:** Improved performance of brake discs: State-of-the-art survey, Chalmers Applied Mechanics, Gothenburg Sweden, 2011, 55 pp.

[13] **Lindecke, R.;**Thermal Behavior of Materials, ME2105

[14] **Neudeck, D.; Wüllner, A.:** Bremsen mit nichtmetallischen Bremsscheiben. In: Breuer,nB.; Bill, K. H. (Hrsg.): Bremsenhandbuch – Grundlagen, Komponenten, Systeme, Fahrdynamik. ATZ/MTZ-Fachbuch, 3. Auflage, Friedr. Vieweg & Sohn Verlag/GWV Fachverlage GmbH, Wiesbaden, 2006

[15] **Raninger, P.; Ecker, W.: .** Projekt A6.15 Modeling of the in-service behavior of wheel-mounted brake disks for railway applications, MCL-A615, Leoben, 2014

[16] **Raninger, P.; Ecker, W.: .** Projekt A6.15 Modeling of the in-service behavior of wheel-mounted brake disks for railway applications, Thermophysical data, MCL-A615-A-P1, Leoben, 2014

[17] **Ristic, N.**: Einfluss der Anbindungsstelle an Spannungen und Verformungen der Bremsscheibe, Siemens RS BG EN SDE BRA, Graz, 2017, (kiadatlan)

[18] **Saumweber, E.; Gerum, E.; Berndt, J.:** Grundlagen der Schienenfahrzeugbremse – Darmstadt, Hestra-Verl., 1990, (Archiv für Eisenbahntechnik ; 43)

[19] **Severin, D.; Franke, U.; Lampic, M.:** Steigerung der Lebensdauer von Bremsscheiben durch beanspruchungskonforme Werkstoffentwicklung und werkstoffgerechte Prüfung. In: ATZ 104 (2002), Nr. 11, S. 1016–1023

[20] **Walz, M / Becker R.:**
The development of cast iron materials for brake discs (Die Entwicklung von Gusseisenwerkstoffen für Bremsscheiben), 1. Internationale Fachtagung CastTec 2012, Die Welt der Gusseisenwerkstoffe - Vielfalt für die Zukunft, Krefeld, DE, 8.-9. Nov, 2012