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Temperaturne razmere v dotikih z jeklenimi in kompozitnimi zavornimi diski C/C-SiC

Surface Temperatures in the Contacts with Steel and C/C-SiC-Composite Brake Discs

Mihael Kermc - Zmago Stadler - Mitjan Kalin

V običajnih serijskih vozilih so zavorni diski izdelani iz jeklene ali sive litine, zavorne ploščice pa so kompozitne, na podlagi veziv iz organskih smol. Izdelovalci vozil snujejo, predvsem v prestižnem in športnem razredu, vse večja in težja vozila z močnejšimi motorji, ki dosegajo velike hitrosti, zaradi česar potrebujejo taka vozila zavorne sisteme večjih zavornih moči kot jih zagotavljajo običajne zavore. Izboljšanje zmogljivosti zavornega sistema se lahko doseže s povečanjem običajnih sistemov, kar ni najustreznejša rešitev, ali z uporabo novih, boljših materialov za zavorne diske in ploščice. Med obetavne materiale, ki se uporabljajo v te namene, sodijo tudi kompozitni diski C/C-SiC. Kljub majhni obrabi in zmožnosti prenašanja velikih zavornih moči, je njihova uporaba zelo omejena zaradi trenutno neustreznih materialov zavornih ploščic, ki bi se lahko uspešno uporabljali v dvojici s temi diski. Eden izmed glavnih razlogov za to je visoka temperatura, ki nastaja v dotikih z diski C/C-SiC. Zaradi posebnosti materialov in zgodnje faze razvoja takih zavornih sistemov pa ustreznih podatkov v literaturi še ni.

Kot prvi korak pri razvoju ustreznih zavornih ploščic, za že znane zavorne diske lastne proizvodnje iz kompozitov C/C-SiC, smo zato najprej raziskali vrednosti temperatur, ki nastajajo na površinah teh diskov in jih primerjali z običajnimi jeklenimi diski. Spremljali smo tudi potek rasti dotikalnih temperatur na dveh različnih preizkuševališčih, na katerih smo lahko simulirali dinamične pogoje zaviranja in ustaljene pogoje ter razlike med diski C/C-SiC in jeklenimi diski razložili z različnimi toplotnimi lastnostmi raziskovanih materialov. V vseh testih smo za material ploščic uporabili kompozit na podlagi kovinske matrice, prav tako lastne izdelave.

(Ključne besede: diski zavorni, litina jeklena, C/C-SiC kompoziti, razmere temperaturne)

Automotive braking systems normally employ conventional or ventilated brake discs and pads. In these systems the brake discs are made of steel or grey cast iron, which are paired with composite "organic" brake pads. Car manufacturers, however, are designing larger and heavier vehicles, with more powerful engines, which results in higher driving speeds and greater demands being placed on the frictional power of the brake systems. Improving the performance of a braking system requires either a larger conventional brake, which is not the best solution, or the use of new, improved brake-disc and pad materials. One such promising material for brake-disc applications is a C/C-SiC composite. However, despite its low wear rate and high frictional power, its use is still very limited because of the lack of an appropriate pad material that will perform well in combination with these discs under the conditions that are experienced with mass-production vehicles. One of the main reasons for this is the supposed high temperatures generated in these contacts. However, since this research is in its early stages and because of the particular materials and their combinations, relevant data on this topic cannot be obtained from the literature.

Our first step in the development of a pad material for our own design of C/C-SiC composite discs was to determine the contact temperature and make a comparison with conventional steel discs under the same conditions. The evolution of the contact temperature was studied using two different testing machines and methods, where we simulated the dynamic braking conditions that are similar to those observed in real applications and under steady-state conditions. The differences could be explained by the thermal properties of the materials. All the experiments used the same pads, which were made from a metal-matrix composite to our own design.

(Keywords: brake discs, steel, C/C-SiC composite, surface temperatures)

0 UVOD

Zavorni sklopi v vozilnih zavornih sistemih so običajno sestavljeni iz kompaktnega ali zračenega zavornega diska in zavornih ploščic [1]. V običajnih, serijskih vozilih so zavorni diski izdelani iz jeklene ali sive litine, zavorne ploščice pa so kompozitne, na temelju veziv iz organskih smol [2]. Te dvojice materialov so tribološko ustrezne za uporabo v zavornih sistemih zmernih obremenitev, saj jih pri tem odlikuje razmeroma visok in stabilen koeficient trenja, majhna obraba ter običajno tiho delovanje ([3] in [4]). Izdelovalci vozil snujejo predvsem v uglednem in športnem razredu vse večja in težja vozila z močnejšimi motorji, ki dosegajo velike hitrosti, zaradi česar potrebujejo taka vozila zavorne sisteme večjih zavornih moči, kakor jih zagotavljajo običajne zavore. Uporaba le-teh je namreč omejena s dotikalno temperaturo ploščic, ki jo določa piroliza veziva, tj. fenolne smole. Pri temperaturi 240 °C začno zato ti materiali izgubljati svoje, prvotno dobre, lastnosti in postanejo neprimerni za uporabo ([5] in [6]).

Izboljšanje zmogljivosti zavornega sistema se lahko doseže z rekonstrukcijo (povečanjem) običajnih sistemov z dimenzioniranjem za večje obremenitve ali z uporabo novih, boljših materialov za zavorne diske in ploščice. Povečanje sedanjih sistemov ima za posledico tudi povečanje mase sistema, kar ponovno zmanjša zmogljivost vozila in prvotno želen učinek. Zaradi tega je sama rekonstrukcija zavornega sistema mogoča le izjemoma - za manjše povečanje zavornih moči, v nekaterih primerih, npr. v športnih modelih serijskih vozil in še posebej v športno-hitrostnih tekmovalnih vozilih, pa je to neustrezen način rešitve, saj je teža zavornih sistemov eden od ključnih parametrov njihove učinkovitosti ter s tem celotnega vozila. Zaradi tega so že v preteklosti uvajali v najzahtevnejše zavorne sisteme predvsem diske iz novejših in sodobnejših materialov. Npr. v zavornih sistemih v letalstvu in avtomobilskih tekmovalnih razredih se uporabljajo kompoziti na podlagi ogljika (kompoziti C/C) ([7] do [10]), v hitrih vlakih ICE kompoziti s kovinskim vezivom (KKV - kompoziti MMC) [11], za uporabo v širši prevozni tehniki pa so bili razviti kompoziti na podlagi ogljika in keramike (kompoziti C/SiC, C/C-SiC), ([12] in [13]).

Kompoziti C/C-SiC so zanimiv in obetaven material za zavorne diske širokega pasu uporabe. Zaradi majhne gostote so diski iz kompozitov C/C-SiC znatno lažji od navadnih kovinskih in primerljivi z diski iz KKV ter C/C ([7], [12] in [13]). Zaradi dobre korozijske in oksidacijske obstojnosti ter odličnih toplotnih lastnosti lahko obratujejo pri nekaj 100 °C višjih temperaturah kakor navadni kovinski diski ali diski iz KKV [14], kar jim omogoča doseganje izjemnih zavornih moči. V primerjavi z diski na podlagi kompozitov C/C pa imajo znatno manjšo obrabo in s

0 INTRODUCTION

Automotive braking systems normally employ conventional or ventilated brake discs and pads [1]. In these systems the brake discs are made of steel or grey cast iron, which are paired with composite “organic” brake pads [2]. These types of friction materials are suitable for use in braking systems with moderate loads, where they exhibit a relatively high and stable friction coefficient, a low rate of wear and are quiet during operation ([3] and [4]). Car manufacturers’ designs of prestige and sports-class vehicles always tend towards larger and heavier vehicles. These vehicles have powerful engines and reach high driving speeds. Accordingly, they need braking systems that provide more braking power compared to conventional braking systems. The use of conventional braking systems is, however, limited by the contact temperature due to the pyrolisis of the phenolic resin bonding material. Consequently, at 240°C the originally good material properties start to deteriorate and the material becomes useless ([5] and [6]).

Improved braking-system performance can be achieved either by a re-design (i.e., an enlargement) of the conventional brake system, in terms of higher loads, or by the use of new, improved brake-disc and pad materials. A simple re-design of conventional braking systems leads to an increase in the mass of the system, thus reducing the vehicle’s performance characteristics, which means that the beneficial effect of the extra performance is significantly diminished or even negated. A re-design is therefore only applicable for a small increase in the braking power and is not at all suitable for sports vehicles and race-class vehicles, where weight is one of the main performance characteristics of the braking system and of the whole vehicle. Accordingly, new brake-disc materials were introduced for braking systems with higher-performance demands: carbon/carbon composites are used in aviation and racing vehicles ([7] to [10]), fast ICE-class trains use metal matrix composites (MMCs) [11], and for uses in general transportation, a variety of fibre-reinforced ceramic composites (C/SiC, C/C-SiC) were developed ([12] and [13]).

C/C-SiC composites are an interesting and promising material for brake discs with a wide range of applications. The low density of C/C-SiC makes them significantly lighter than classic steel discs and comparable with Al-MMCs and C/C composite brakes ([7], [12] and [13]). Because of their good corrosion and oxidation resistance and their thermal properties, C/C-SiC brake discs can operate at several hundreds of °C higher temperatures than ordinary steel or Al-MMC composite discs [14], which means they can provide much more braking power. When compared to C/C brake discs, the wear of C/C-SiC discs is significantly lower and the lifetimes accordingly tem daljšo dobo trajanja [15]. Zaradi teh prednosti se kompoziti C/C-SiC izkazujejo kot najbolj obetajoč material zavornih diskov za uporabo, poleg športno-hitrostnih vozil, v katera se že redno vgrajujejo, tudi v serijskih vozilih športnega in višjega cenovnega razreda.

Razvoj zavornih sistemov terja poleg ustreznega materiala diskov tudi le-tem tribološko prilagojen material zavornih ploščic, saj mora tak sistem zagotavljati visok in stabilen koeficient trenja v vsem območju delovanja, dobre protiobrabne lastnosti, ustrezne dotikalne razmere, ki ne povzročajo vibracij in hrupa, čim manjšo občutljivost za vlago in vodo idr. Trenutno so v uporabi zavorne ploščice iz treh različnih skupin materialov, in sicer na podlagi materialov z organskimi vezivi, kompozitnih materialov C/C ter KKV. V dosedanjih raziskavah je bilo ugotovljeno ([16] in [17]), da sedanji materiali zavornih ploščic, ki so bili posebej razviti za uporabo v navadnih, KKV ali zavornih sistemih C/C, ne zagotavljajo ustreznih triboloških lastnosti tudi v dotikih z diski iz kompozitov C/C-SiC ter s tem povezanih delovnih lastnosti celotnega zavornega sistema. Zaradi tega so materiali za zavorne ploščice v zavornem sistemu z diski C/C-SiC šibki člen in omejujejo njihovo širšo uporabo ter še posebej uporabo v serijskih vozilih. Med znanimi materiali za zavorne ploščice dosegajo še najboljše rezultate kompoziti na podlagi kovinske matrice in se kljub številnim pomanjkljivostim glede obrabe in hrupa uporabljajo v športnih motociklih [18], zato smo jih izbrali kot temelj za naše raziskave in razvoj.

Dosedanje izkušnje in literatura o triboloških lastnostih v dotikih s kompoziti C/C-SiC, še posebej pri velikih obremenitvah, nakazujejo, da je predvsem precej višja temperatura na dotikalnih površinah pri teh sistemih, v primerjavi z običajnimi kovinskimi diski, razlog za neustrezne lastnosti in uporabo vrste protimaterialov za zavorne ploščice [17]. Podrobnih analiz o višini dotikalnih temperatur in neposredne primerjave z materiali iz običajnih zavornih sistemov pa v literaturi nismo našli. Zaradi potrebe po podrobnejšem poznavanju temperaturnih razmer in njihove morebitne ključne vloge pri razvoju tribološkega sistema med kompoziti C/C-SiC in KKV smo v tem delu raziskali temperaturne razmere v dotikih med kompozitnimi diski C/C-SiC in zavornimi ploščicami na podlagi kompozita s kovinskim vezivom ter jih primerjali z razmerami v dotikih med običajnimi jeklenimi diski in enakimi ploščicami na podlagi kompozita s kovinskim vezivom. Temperaturne razmere smo raziskovali s standardnim preizkusom, s katerim smo skušali simulirati delovanje in razmere pri zaviranju dejanskega zavornega sistema, ter modelnega preizkusa, s katerim smo ugotavljali vpliv toplotnih lastnosti materialov na dotikalno temperaturo obeh sistemov v ustaljenih razmerah.

longer [15]. All of these advantages make C/C-SiC composites the most promising material for the brake discs of racing vehicles, where they are already in use, but also for the serial production of prestige and sports vehicles.

However, the development of an automotive braking system requires a brake-disc material with a tribologically matched brake-pad material. The whole system must provide a high and stable friction coefficient across the whole operating range, as well as good wear resistance, appropriate contact conditions that do not generate noise and vibration, low humidity and water dependence/sensitivity, etc. Presently, three different types of brake-pad materials are in use: organic, C/C and MMCs. Earlier studies ([16] and [17]) showed that existing brake-pad materials developed for use with ordinary steel, Al-MMCs or C/C composite brake discs do not provide the proper tribological behaviour in the contact with C/C-SiC composite brake discs, and therefore the performance of the brake system is not satisfactory. Accordingly, the brake-pad material represents a weak point in the C/C-SiC brake system and causes major limitations in the use of these systems in serial vehicle production. Among the various brake-pad materials available, metal-matrix composites show the best results and are, despite their deficient wear and noise properties [18], already in use for sports-motorcycle braking systems. Therefore, we decided to use this material as a starting material for our research and development of a new tribological system for brakes.

Early investigations and the literature data about the tribological properties in contacts with C/C-SiC composite brake discs show that, particularly at higher loads, a significantly higher contact temperature compared to conventional steel discs is the main reason for the poor performance and the reduced choice of possible brake-pad materials in contacts with C/C-SiC composite brake discs [17]. We could not find any publications referring to contact temperatures in C/C-SiC brake discs and their comparison with conventional braking systems. However, such data could be very important for the development of a C/C-Si–MMC tribological system. Therefore, in our study, temperatures in the contact of C/C-SiC composite brake discs with MMC brake pads were investigated and compared with the temperatures generated in the contacts of conventional steel brake-disc and the same MMC brake-pad materials. The surface temperatures were studied by using two different experimental devices and procedures: i.e., a standard test, where operation under real braking conditions was simulated; and a model test, where the influence of the thermal properties on the contact temperature under stationary conditions was studied.

1 EKSPERIMENTALNO DELO

1.1 Materiali

V raziskavi smo za vzorce uporabili zavorne diske in zavorne ploščice enakih izmer, kakršne se vgrajujejo v špotno-tekmovalne motocikle. Prvi tip zavornih diskov (MS Production, Bled, Slovenija) je bil izdelan iz kompozita C/C-SiC premera 320 mm in debeline 7 mm. Slika 1 prikazuje prerez diska v bližini površine. Nosilno jedro je izdelano iz 2D kompozita C/C, ki ohranja mehanske lastnosti tudi pri povišanih temperaturah, do 1400 °C. Kompozitno jedro je prekrito s plastjo reakcijsko sintranega SiC [12]. Debelina plasti SiC na dotikalnih površinah znaša 400±20μm. Površinska plast SiC se nadaljuje v mešano plast SiC in C/C ter postopoma preide v čisti kompozit C/C na globini 550±20μm pod površino. Drugi tip diskov, ki smo jih uporabili, so bili običajni jekleni diski (DP320/6, Brembo, Bergamo, Italija) premera 320 mm in debeline 6 mm. Vse preizkuse smo opravili z zavornimi ploščicami izmer 78 x 26 mm, izdelanimi na podlagi kompozita s kovinskim vezivom (tip 4035, MS-Production, Bled, Slovenija).

1.2 Standardni preizkus

V raziskavi smo uporabili dve vrsti preizkusov. Prvi je bil standardni preizkus, s katerim simuliramo delovanje in razmere na zavornih površinah pri zaviranju dejanskega zavornega sistema. Testi so bili opravljeni na

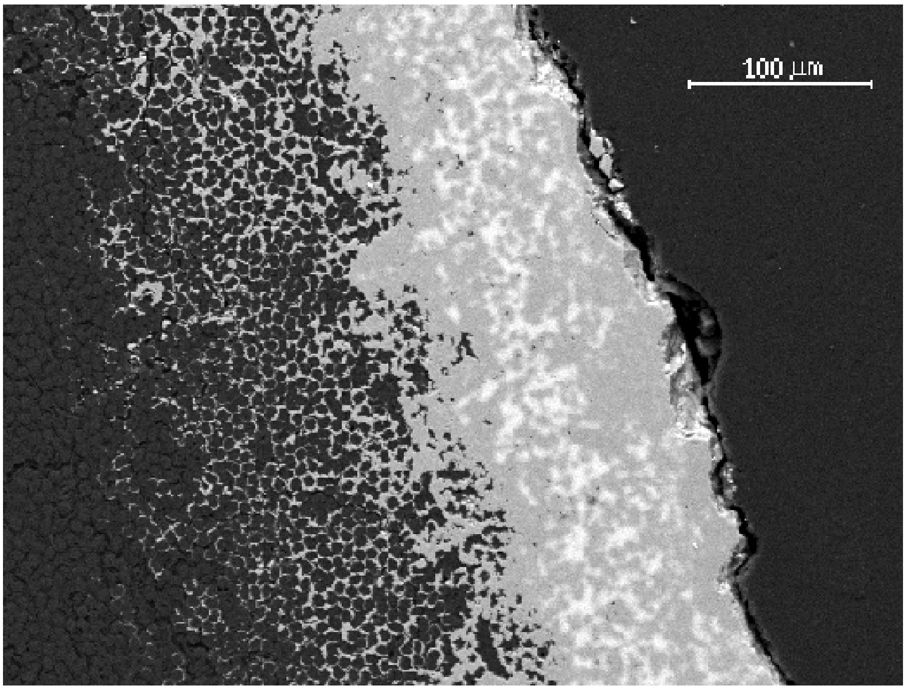
1 EXPERIMENTAL WORK

1.1 Materials

For the research, brake discs and pads with the same dimensions as used in racing motorcycles were used. One type of discs (MS Production, Bled, Slovenia) was made of a C/C-SiC composite material. The diameter of the disc was 320 mm and the thickness was 7 mm. Figure 1 shows a section of the disc near the surface. The supporting core is made of a 2D C/C composite that maintains its mechanical properties even at elevated temperatures, up to 1400°C. The core is covered with a reaction-bonded SiC layer [12]. The layer thickness on the contact surfaces is 400±20μm. The surface's "pure" SiC layer gradually changes with depth from the surface to a mixed layer of C/C and SiC and further on to a pure C/C matrix at 550±20μm below the surface. The second type of brake disc was conventional steel brake discs (DP320/6, Brembo, Bergamo, Italy), with a diameter of 320 mm and a thickness of 6 mm. All the tests were performed by using the same type of MMC brake pads, with dimensions of 78 x 26 mm (MS Production, Bled, Slovenia).

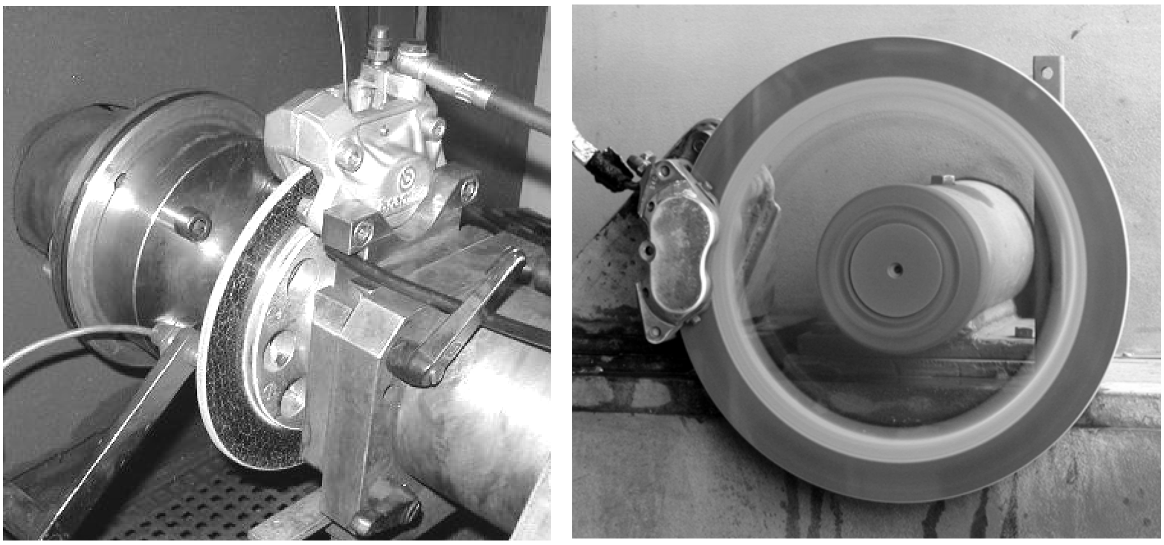
1.2 Standard testing procedure

Two different testing procedures were used. The first was a standard procedure, where the operating and contact conditions of a real braking system were simulated. The tests were performed on a standard KRAUSS RWS75B (Krauss G.m.b.H., Murr, Germany)



Sl. 1. *Mikrostruktura prereza zavornega diska iz C/C-SiC kompozita v bližini površine*

Fig. 1. *Microstructure of C/C-SiC composite brake disc section near surface*



a) b)

Sl. 2. *Shematski prikaz (a) standardnega preskuševališča KRAUSS RWS75B ter (b) modelnega preskuševališča MS-P.*

Fig. 2. *Shematic view of (a)standard testing machine KRAUSS RWS75B and (b)model testing machine MS-P.*

preizkuševališču KRAUSS RWS75B (Krauss G.m.b.H., Murr, Nemčija) v skladu z 8. odstavkom, navodila ECE-R90 Združenih narodov [19], ki predpisuje postopke preskušanja zavornih lastnosti na napravah za preizkušanje. Test je sestavljen iz dveh faz. Prva faza je namenjena zgolj utekanju/prilagajanju dotikalnih površin. Poteka pri hitrosti 5,8m/s ter tlaku 1,16MPa. Sestavljena je iz 30 zaviranj, pri čemer temperatura diska ne sme preseči 250 °C, sicer je potrebno ohlajanje na 50 °C. Sledi druga faza, ki pomeni dejansko preizkušanje za vrednotenje rezultatov. V fazi preizkušanja se izvede šest krat po deset zaviranj, skupaj 60 zaviranj. Posamezen cikel zaviranja je sestavljen iz 5 s zaviranja in 10 s prostega teka pri stalni drsni hitrosti 5,8 m/s ter tlaku 1,16 MPa. Med posameznimi sklopi testa je treba disk ohladiti na 100 °C. Temperature diska se v skladu s postopkom [19] merijo s termoelementom v drsni izvedbi na površini diska ob izstopu iz dotika z zavorno oblogo. Uporabljeno standardno preizkuševališče je shematsko prikazano na sliki 2a.

1.3 Modelni preizkus

Drugi tip preizkusa v tej raziskavi je bil modelni preizkus, s katerim smo želeli ugotoviti končno temperaturo zavornih površin pri ustaljenih pogojih in primerjati vrednosti pri obeh dvojicah materialov ter ugotoviti vpliv toplotnih lastnosti materialov na razvoj temperaturnega stanja. Za dosego tega cilja je bilo treba izbrati novo preizkuševališče, saj predpisana oprema in postopek po [19] ne zagotavljata pogojev za doseganje

testing machine in accordance with Annex 8 of the United Nations ECE-R90 regulation [19], where the determination of friction behaviour by machine testing is regulated. The test consists of two phases. The first phase is the running-in procedure, which is necessary to adapt/ conform the contacting surfaces. The speed in this stage is 5.8 m/s, and the pressure 1.16 MPa. It comprises 30 braking cycles. The complete loading and un-loading of the contact is considered as a braking cycle. If the disc temperature exceeds 250°C during the running-in, cooling of the disc to 50°C is required. The first phase is followed by the second phase, which represents the actual testing for the evaluation of the results. In the second phase, six groups of ten braking cycles, a total of 60 cycles, are performed. Each braking cycle consists of 5 seconds of braking and 10 seconds of free run at a constant sliding speed of 5.8 m/s and a pad pressure of 1.16 MPa. After every 10 cycles a cooling period is required to allow the disc temperature to reach 100°C. In accordance with the procedure in [19], the disc temperature is measured with a thermocouple sliding on the disc surface at the exit from the pad-disc contact. The standard testing machine used for our experiments is shown in Figure 2a.

1.3 Model testing procedure

The second type of testing was a model testing procedure. The purpose of this test was to determine the temperature of the contacting surfaces under stationary sliding conditions, and to compare the values for both disc materials in order to determine the influence of thermal properties on the disc's surface temperatures. To achieve this goal, a different testing procedure had to be chosen, because the standard equipment and procedure according to [19] do not ensure the ustaljene temperaturne ravni. Modelni testi so bili zato izvedeni na lastnem preizkuševališču zavornih sistemov MS-P [20], ki je v zasnovi podobno znanim sorodnim preizkuševališčem [21], in je shematsko prikazano na sliki 2b.

Pred začetkom dejanskega preizkusa smo, podobno kakor pri standardnem testu, opravili fazo utekanja/prilagajanja dotikalnih površin. Pri utekanju smo uporabili enak osnovni cikel zaviranja kakor pri standardnem testu, torej 5 s zaviranja in 10 s prostega teka, v preizkusu pa je bil cikel sestavljen iz 5 s zaviranja in 5 s prostega teka, s čimer smo lahko hitreje povišali dotikalno temperaturo. Utekanje je zajemalo enako kakor v standardnem testu 30 ciklov zaviranj, dejanski preizus pa 20 ciklov zaviranj. Pri tem številu zaviranj smo pri obeh raziskovanih dvojicah materialov dosegli ustaljeno temperaturno stanje. Preizkus je potekal pri stalni drsni hitrosti 26 m/s ter tlaku približno 0,8 MPa.

Za meritev temperature smo uporabili vgradni termoelement, ki smo ga vstavili v mirujočo zavorno ploščico na globini približno 300 μm pod površino. S tem smo se skušali čim bolj približati meritvam »dejanske dotikalne« temperature na zavornih površinah.

2 REZULTATI

Slika 3 prikazuje rezultate dveh meritev temperature na disku iz kompozita C/C-SiC v dotiku s ploščico iz kompozita MMC, izvedenih na standardnem preizkuševališču. Krivulje poteka

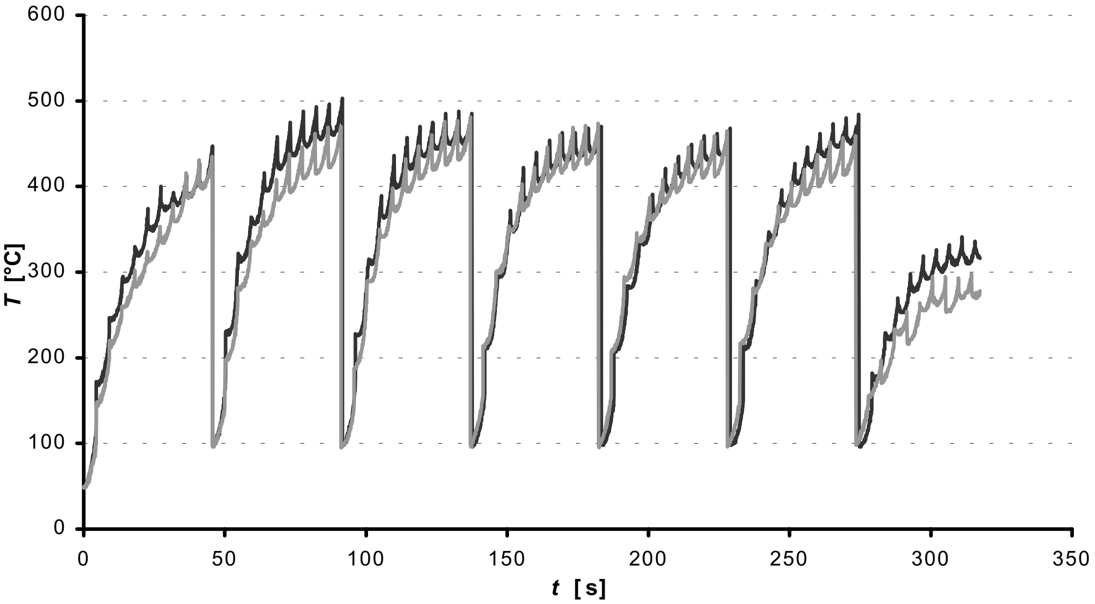
conditions for the build-up of stationary temperature conditions. Model tests were therefore performed on a self-built MS-P testing machine [20], which has a similar design to other existing testing machines [21], and is schematically shown in figure 2b.

The testing procedure was, like the standard testing procedure, composed of two phases. At the beginning there was a running-in phase where the contact surfaces were adapted. The running-in phase contained 30 braking cycles of 5 seconds of braking followed by 10 seconds of free run, the same as in the standard test. In the second phase, which was used for the evaluation of the results, the braking cycle was partially modified. The adjusted cycle was composed of 5 seconds of braking and 5 seconds of free run, which allowed us to raise the contact temperature more rapidly and to achieve the stationary conditions faster. Accordingly, only 20 braking cycles were needed to obtain the stationary temperature level. The test was performed at a constant sliding speed of 26 m/s and a pad pressure of 0.8 MPa.

For the temperature measurement a thermocouple built into a stationary brake pad and positioned approximately 300 μm below the contact surface was used. In this way we tried to measure the "real contact" temperature as close as possible to the braking contact surface where the heat is generated.

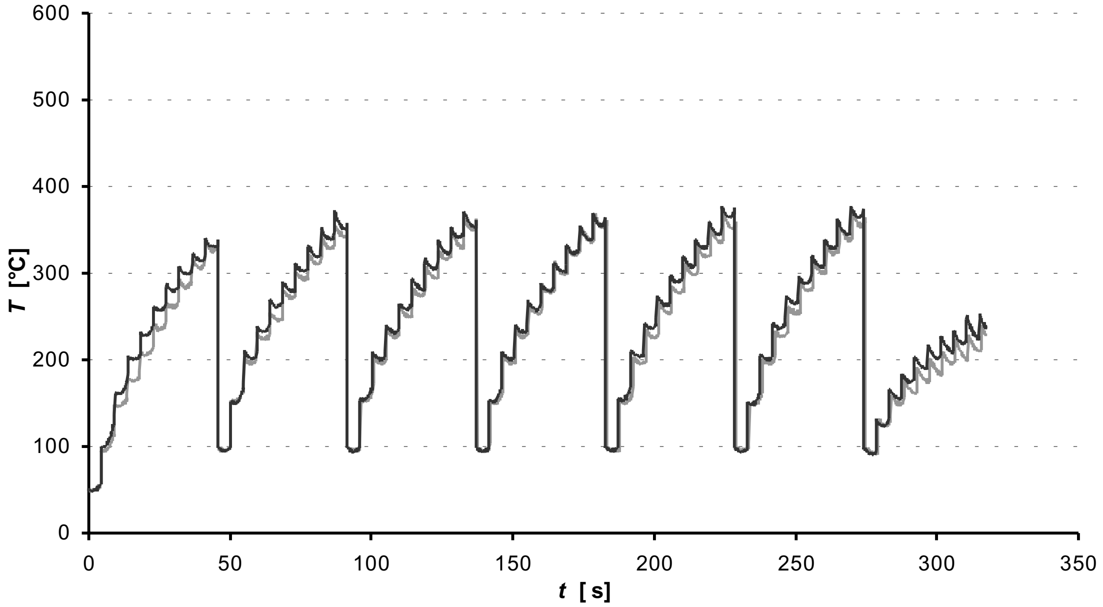
2 RESULTS

Figure 3 shows the results of the two temperature measurements on the C/C-SiC composite brake disc in contact with MMC composite brake pads performed on a standard testing machine. It is clear that in each group of



Sl. 3. *Diagram poteka temperature v odvisnosti od časa preskusa (standardni preskus, disk C/C-SiC, ploščica 4035, v=5,86m/s, p=1,16MPa). Digram prikazuje rezultate dveh preskusov.*

Fig. 3. *Graph of measured temperature over time of measurement (standard test, disc material C/C-SiC, pad 4035, v=5,86m/s, p=1,16MPa). Graph represents results from two measurements.*



Sl. 4. *Diagram poteka temperature v odvisnosti od časa preskusa (standardni preskus, disk jeklo, ploščica 4035, v=5,86m/s, p=1,16MPa). Digram prikazuje rezultate dveh preskusov.*

Fig. 4. *Graph of measured temperature over time of measurement (standard test, disc material steel, pad 4035, v=5,86m/s, p=1,16MPa). Graph represents results from two measurements.*

temperature v vseh spletih zaviranj se dvigujejo dokaj hitro do temperature približno 400 °C, nato pa se krivulje zravnajo, kar nakazuje na približevanje ustaljenim pogojem. Pojav je še posebej izrazit v zadnjih petih sklopih. Kljub temu ustaljeni pogoji v nobenem primeru niso bili doseženi, saj je v skladu z [19] vedno prej sledil vmesni prosti tek z ohlajanjem diska na 100°C. Najvišje dosežene temperature v posameznih sklopih se razlikujejo za 70 °C, vendar pa je bila ponovljivost rezultatov posameznih sklopov zelo dobra, običajno boljša od 10% odstopanj. Najvišja izmerjena temperatura na površini diska je bila 480 °C.

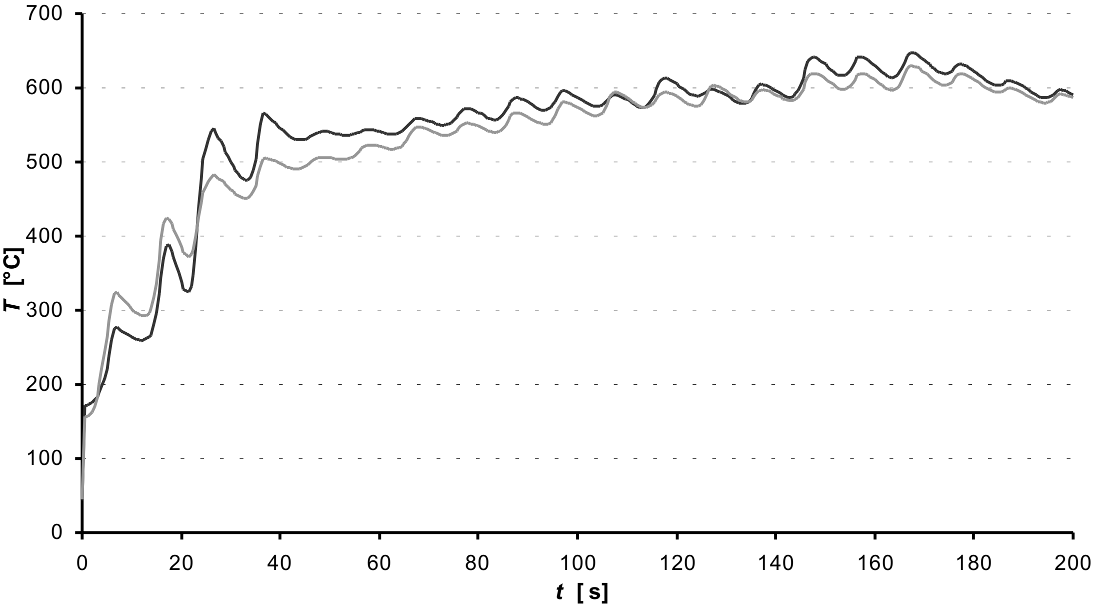
Slika 4 prikazuje rezultate dveh meritev temperature na jeklenem disku v dotiku s ploščico iz kompozita MMC, izvedenih na standardnem preizkuševališču. Krivulje poteka temperature v posameznem sklopu zaviranj so precej različne od krivulj pri disku C/C-SiC. Krivulje so v tem primeru veliko bolj položne in skoraj ravne. Na koncu vsakega sklopa še ni zaznati približevanja ustaljenim pogojem. Najvišja temperatura v posameznem krogu se povečuje in doseže najvišjo temperaturo pri teh pogojih v zadnjem, šestem sklopu, 370 °C. Razlika najvišjih temperatur, doseženih v posameznem sklopu, je za polovico manjša kakor v primeru diskov C/C-SiC (sl. 3), 35 °C. Ponovljivost izmerjenih rezultatov je izjemno dobra, boljša od 5 % odstopanj.

Na sliki 5 vidimo rezultate meritev temperature pod površino ploščice MMC v dotiku z diskom C/C-SiC pri preizkusu na modelnem preizkuševališču. Prikazani so rezultati dveh meritev,

braking cycles the temperature rises relatively quickly until a temperature of approximately 400°C is reached, but then the curves flatten out slightly, which indicates an approach to constant-temperature conditions. This phenomenon is particularly clear in the last five braking-cycle groups. However, the constant-temperature conditions were not observed in any of the braking-cycle groups because, according to the ordinances [19], the free-run cycle with cooling the disc down to 100°C interrupts the frictional heating process. The highest temperatures achieved in these six groups varied by about 70°C, yet the repeatability of the results in separate groups was very good: in general with a deviation of less than 10%. The highest measured temperature was 480°C.

Figure 4 shows the results of two temperature measurements on a steel brake disc in contact with MMC composite brake pads, performed on a standard testing machine. The shape of the temperature curves in each braking-cycle group is different from those obtained with the C/C-SiC brake disc. In this case the curves are not so steep and almost linear. Even at the end of each braking group there are no indications of approaching the constant-temperature level. The highest temperature measured in each group increases in every subsequent group, and is highest in the last (the sixth) group, reaching 370°C. The variation in highest measured temperatures in every braking-cycle group is only half as high as the variation in the C/C-SiC composite brake discs (Figure 3), i.e., 35°C. The repeatability of the measured results is very good, with a deviation of less than 5%.

Figure 5 presents the results from the temperature measurement beneath the contact surface in the MMC brake pad in contact with the C/C-SiC brake disc, performed on a model-testing machine. The results



Sl. 5. *Diagram poteka temperature v odvisnosti od časa preskusa (modelni preskus, disk C/C-SiC, ploščica 4035, v=26,14m/s, p=0,44MPa). Digram prikazuje rezultate dveh preskusov.*
Fig. 5. *Graph of measured temperature over time of measurement (model test, disc material C/C-SiC, pad 4035, v=26,14m/s, p=0,44MPa). Graph represents results from two measurements.*

ki potrjujejo zelo dobro ponovljivost rezultatov preizkusov. Vidimo, da je krivulja zelo strma, kar pomeni zelo hiter dvig dotikalne temperature do približno 550 °C, nato pa veliko počasneješe in umirjeno povečevanje do približno 600 °C, ko je temperatura ostala nespremenljiva. Gradient povečevanja temperature na začetku preizkusa, v prvih štirih ciklih, je znašal približno 30 K/s. Ti rezultati so v tem smislu podobni rezultatom, dobljenim na standardnem preizkuševališču, za katere je bil tudi značilen strm dvig temperature in kasnejše počasno približevanje ustaljenim razmeram.

Potek krivulje temperature v dotikih z jeklenimi diski, merjenimi na modelnem preizkuševališču, prikazuje slika 6. Temperatura je naraščala znatno počasneje kakor v primeru enakih preizkusov z diski C/C-SiC in je v prvih štirih ciklih znašala le 10 K/s. Po približno 10 ciklih je temperatura dosegla najvišjo vrednost, približno 550 °C, nato pa se je začela počasi zniževati, vse do ustaljenih razmer pri približno 420 °C. Čeprav so rezultati meritev temperature v prvem delu testa podobni kakor na standardnem preizkuševališču, tj. razmeroma počasno višanje temperature, pa lahko v tem primeru vidimo, da se pred doseženim ustaljenim stanjem temperatura zniža. Tak potek krivulje dotikalne temperature je povsem različen od poteka pri dotikih z diski C/C-SiC pri enakih razmerah preizkušanja, kar nakazuje na znatne razlike med raziskovanima dvojicama materialov.

3 RAZPRAVA

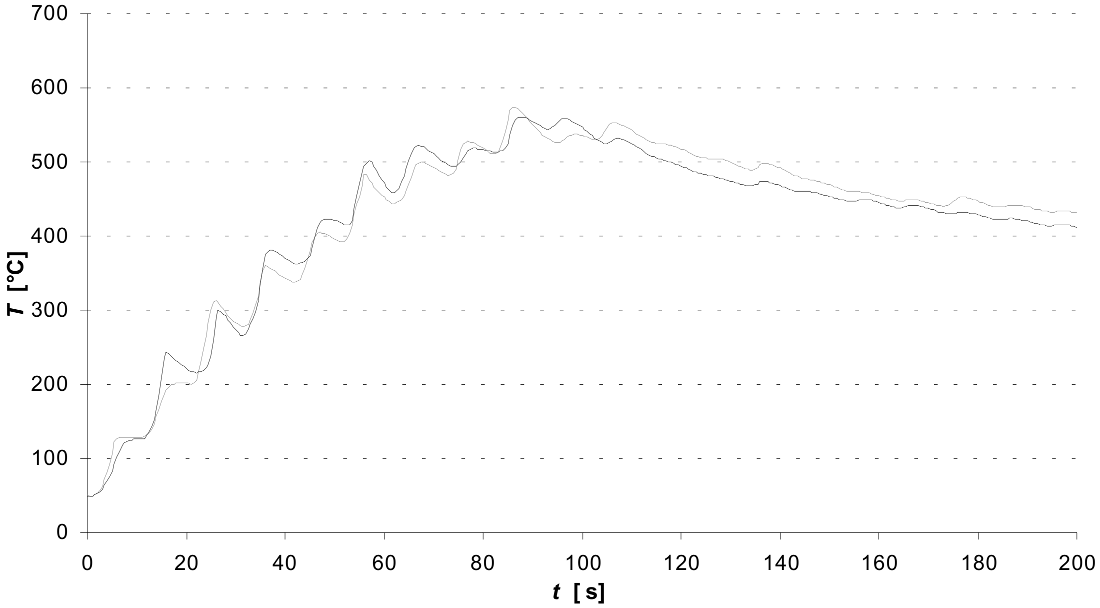
Iz dosedanjih raziskav je bilo ugotovljeno, da ima temperatura na zavornih površinah velik pomen

from two measurements indicate very good repeatability of the results. The curves are very steep, which indicates a rapid increase in the contact temperature up to approximately 550°C. After reaching this level the increase is slower, and the temperature gradually increases to approximately 600°C, where it remains constant. At the beginning of the test (in the first four braking cycles), the gradient of the temperature increase was approximately 30 K/sec. These results are similar to the results obtained from the tests on the standard testing machine, where a steep rise and a subsequent gradual approach to constant-temperature conditions was also measured.

The course of the temperature graphs measured on the steel brake discs using the model-testing machine is shown in Figure 6. The temperature increase was much slower than for the C/C-SiC composite brake discs, and the gradient in the first four cycles was only 10 K/sec. After approximately 10 cycles the temperature reached its highest value, approximately 550°C, and then started to decrease until the constant-temperature level was restored at approximately 420°C. In the first part of the test the results are similar to the results obtained using the standard testing machine, i.e., a moderate temperature increase. However, in the second part of the tests they are different, showing a decrease in the temperature before the constant-temperature level is reached. Such a variation in temperature is also completely different from the one obtained with the C/C-SiC brake discs, which indicates significant, inherent differences between the material couples in this study.

3 DISCUSSION

Earlier studies on different brake materials showed that the surface temperature has a significant



Sl. 6. *Diagram poteka temperature v odvisnosti od časa preskusa (modelni preskus, disk jeklo, ploščica 4035, v=26,14m/s, p=0,44MPa). Digram prikazuje rezultate dveh preskusov.*
Fig. 6. *Graph of measured temperature over time of measurement (model test, disc material steel, pad 4035, v=26,14m/s, p=0,44MPa). Graph represents results from two measurements.*

pri doseganju ustreznih tornih in obrabnih lastnosti za uporabo različnih dvojic materialov v zavornih sistemih ([3], [5] do [9]). Nekateri materiali imajo odlične lastnosti pri zmernih obremenitvah in temperaturah, a so pri povišanih temperaturah povsem neprimerni ([5] in [6]), velja pa tudi nasprotno ([7] do [10]). Zaradi tega je poznavanje temperaturnega stanja in njegova povezava predvsem s toplotnimi lastnostmi materialov izjemno pomembna pri razvoju zavornih sistemov. To še posebej velja za sodobnejše kompozitne materiale na podlagi ogljika in/ali keramike, ki imajo precej različne toplotne in tudi druge lastnosti od običajnih kovinskih materialov. Razvoj zavornih sistemov z uporabo C/C-SiC in podobnih sorodnih materialov je še v začetnem obdobju, tako da dostopnih podatkov o triboloških lastnostih in z njimi povezanih temperaturnih stanj ustreznih dvojic materialov še ni. V tej raziskavi smo zato primerjali temperaturno stanje na zavornih površinah diskov iz kompozita C/C-SiC in običajnih jeklenih diskov v dotikih s ploščicami na podlagi kompozita s kovinsko matrico. Uporabili smo dve vrsti preizkuševališč. S preskusi na standardnem preizkuševališču (KRAUSS RWS75B) smo skušali pridobiti primerljive podatke za standardne pogoje preizkusov, v katerih se simulira dejansko delovanje in razmere zavornih sistemov, na modelnem preizkuševališču MS-P [20] pa smo skušali narediti primerjavo temperature na površinah v ustaljenih razmerah in ugotoviti vpliv toplotnih lastnosti izbranih materialov na razvoj temperaturnega stanja.

Rezultati kažejo precej različno obnašanje in doseganje precej različnih temperaturnih ravni na zavornih površinah. V primeru diskov iz kompozitov

effect on the optimum friction and wear properties of braking systems ([3], [5] to [9]). Some materials exhibit excellent performance under moderate loads and temperatures but are entirely inappropriate at higher temperatures ([5] and [6]), and vice-versa ([7] to [10]). Therefore, knowledge of the surface-temperature conditions and their relation to the thermal properties of the materials is very important for the development of braking systems. This is especially true for modern carbon- and/or ceramic-based composite materials, where the thermal and other properties vary considerably from those of conventional metal materials. The development of braking systems with C/C-SiC and similar composite materials is still in its early stages, and therefore there is no available information on the tribological properties and the related temperature conditions in the contacts with any other materials that are suitable for brake applications. Therefore, in this study the temperature conditions on the surfaces of the C/C-SiC composite and the steel brake discs in contact with MMC-based brake pads were compared. Two types of testing machines were used. By using a standard machine (KRAUSS RWS75B) we tried to acquire comparable data for standard testing conditions, where realistic operating conditions are simulated, whereas by using our own, self-designed model machine MS-P [20] we tried to compare the surface temperatures under stationary conditions and study the effect of the thermal properties on the surface-temperature change of selected materials.

The results show very different behaviour and different temperature levels on the braking surfaces with C/C-SiC composite or steel discs. In

C/C-SiC (sl. 3 in 5) se izmerjene temperature zavornih površin povišujejo precej hitreje kakor v primeru jeklenih diskov (sl. 4 in 6) in tudi dosežejo precej večje vrednosti. Kljub dvema različnima postopkoma testiranja in načinom meritve temperature je bilo to jasno izraženo v vseh preizkusih. Temperaturni gradienti na začetku meritev so bili v primeru diskov iz kompozitov C/C-SiC kar trikrat večji kakor pri jeklenih diskih. Razlog za tako obnašanje gre v veliki meri iskati prav v toplotnih lastnostih obeh materialov, saj je toplotna prevodnost pri jeklenem disku dvakrat večja (14 W/mK) kakor pri površinski plasti SiC v disku C/C-SiC (7 W/mK). Razlike v toplotnih lastnostih pa še veliko bolj poudari jedro C/C kompozitnega diska, ki ima, v odvisnosti od usmerjenosti vlaken, v nekaterih smereh toplotno prevodnost samo 1 W/mK [22]. Zaradi tega se pri diskih C/C-SiC večina nastale torne toplote zadrži na površini, kjer se zaradi tega močno poviša temperatura. Zaradi »toplotno izolativnih« lastnosti se toplota ne prevaja v notranjost diska in zato se temperatura tudi v ustaljenem stanju ne zniža (sl. 5).

V nasprotju s tem pa je dvig temperature pri jeklenih diskih precej počasnejši in doseže nižje vrednosti (sl. 4, 6). Toplotne lastnosti jeklenih diskov omogočajo precejšen prevod nastale torne toplote v notranjost diska. Zato je akumulacija na površini manjša, s tem pa je tudi dotikalna temperatura nižja. V standardnem testu je bila temperatura na površini jeklenega diska kar za 110 °C nižja kakor pri kompozitnem disku C/C-SiC, oziroma približno 25 %, merjeno v °C. Še bolj očitno se je razlika v toplotnih lastnostih obeh dvojic materialov pokazala pri modelnem testu, pri katerem se je temperatura po razmeroma počasnem dvigu, do približno 550 °C, v preostalem delu preizkusa precej znižala: na stalnih 420 °C, kar kaže na zmožnost zelo dobrega prevoda toplote v notranjost diska. V tem primeru je bila temperatura skoraj za 200 °C nižja kakor pri disku C/C-SiC v enakih razmerah testiranja.

Iz tega izhaja, da pri zmernih obremenitvah dosegajo temperature v dejanskih sistemih z jeklenimi diski razmeroma nizke vrednosti, še posebej pri zgolj krajših zavornih ciklih (primerljivih s prvim delom krivulje v vsakem sklopu zaviranj na standardnem preizkuševališču), saj se toplota učinkovito prevaja v notranjost diska. Po naših rezultatih v standardnem testu, ki simulira »preobremenitev«, vendar pri pogojih obratovanja navadnih zavor, so te temperature precej pod 300 °C (sl. 4), kar se dobro ujema tudi z dejanskimi razmerami in omejitvami temperature popuščanja organskega veziva v zavornih ploščicah, tj. približno 240 °C ([5] in [6]). Zaradi teh lastnosti je seveda izbira ustreznih materialov zavornih ploščic za jeklene diske dokaj široka.

V nasprotju z obnašanjem pri jeklenih diskih pa že v kratkih zavornih ciklih pri standardnem testu

the case of C/C-SiC composite brake discs (Figures 3 and 5), the temperatures increase much faster than with steel discs (Figure 4 and 6), and they also reach higher values. This was noticeable in all the tests, despite using two different testing procedures and temperature-measurement methods. The gradient of the temperature increase was three times higher in the contacts with C/C-SiC than with the steel discs. The reason for such behaviour can be explained in terms of the thermal properties of the two materials. The thermal conductivity of the steel is three times lower than that of the SiC surface layer of the C/C-SiC composite. This difference is even more pronounced by the extremely low thermal conductivity of the C/C composite core, which can vary with the fibre orientation, and can have a value only of 1 W/mK in some directions [22]. Therefore, the major part of the generated heat is retained in the surface layer, thus the temperature increase at the surface is very high. Because of the "thermally isolative" properties the heat is poorly conducted into the disc subsurface/bulk and therefore even under stationary conditions the surface temperature remains high, without any decrease being observed (Figure 5).

In contrast, the temperature increase on the steel discs is much slower, and lower values are obtained (Figure 4 and 6). The thermal properties of the steel discs enable considerable conduction of generated heat to the interior of the disc and therefore the accumulation of the heat on the surface is lower and consequently the contact temperature is also lower. Using the standard test the surface temperature on the steel disc was 110°C, or approximately 25% (measured in °C) lower than on the C/C-SiC composite disc. The difference in the thermal properties of both materials was even more obvious from the results obtained using the model tests, where the temperature on the steel disc, after a rather slow increase to 550°C, even decreased and stabilized at 420°C, indicating good conduction to the interior of the disc. In this case the temperature was nearly 200°C lower than on the C/C-SiC disc under the same testing conditions.

Hence it follows that in braking systems with a steel disc under moderate loads the temperatures reach relatively low values, especially during shorter braking cycles (comparable with the first part of the temperature curve in every braking-cycle group on the standard test), because of the effective heat transfer into the disc interior. Based on our results from the standard test, which simulates "overload", but for realistic operating parameters, these temperatures reach values significantly below 300°C (Figure 4). This corresponds well with the actual conditions and limitations of the organic matrix in a conventional brake-pad material, i.e., approximately 240°C ([5] and [6]). Therefore, these properties allow a broad selection of suitable brake-pad materials for conventional braking systems using steel discs.

In contrast to the steel discs, the C/C-SiC discs reach relatively high surface temperatures, over 400°C v dotikih z diski C/C-SiC zaradi akumulacije torne toplote predvsem na površini diskov in zaradi tega velikih gradientov površinske temperature, le-ta doseže vrednosti prek 400 °C (sl. 3). V primeru daljših zavornih ciklov in predvsem večjih obremenitev, za katere naj bi se diski C/C-SiC uporabljali, pa bi temperature dosegle še precej višje vrednosti, kar jasno nakazujejo rezultati z modelnega preizkuševališča (sl. 6), kjer smo se omenjenim pogojem bolj približali. Po 25 sekundah preizkusa v treh zavornih ciklih je namreč temperatura v primeru dotika z diskom C/C-SiC dosegla kar 550 °C (sl. 5). Torej, pri teh, bolj ostrih pogojih lahko ponovno ugotovimo, da je nevarnost pregrevanja v dotikih z diski iz kompozita C/C-SiC bistveno večja kakor pri jeklenih diskih. Kljub doseženim višjim temperaturam, se tudi tu pri jeklenih diskih temperatura dviga umirjeno, precej počasneje kakor lahko pričakujemo v dejanskem zavornem sistemu, in v enakem primerjalnem času, tj. po 25 sekundah preizkusa v treh zavornih ciklih, doseže le 250 °C (sl. 6) - kar 300 °C manj kakor v primeru diska iz kompozita C/C-SiC (sl. 5).

Dodaten pokazatelj pričakovanih zelo visokih temperatur v dotikih z kompoziti C/C-SiC pa je dejstvo, da smo na modelnem preizkuševališču merili temperaturo 300 μm pod zavorno površino, kar je razmeroma blizu vira torne toplote. Znano pa je, da je zaradi nastanka torne toplote na površini zato dvig temperature na površini znatno večji kakor pod površino in se lahko v določenih razmerah temperatura v prvih nekaj 10 do 100 μm zniža kar za več 100 °C ([23] do [25]). Poleg tega meritve »dotikalnih« temperatur pod površino (ali zunaj dotika na površini) zaradi fizikalnih omejitev temperaturnih zaznaval izkazujejo nižje vrednosti od dejanskih ([26] do [30]). Iz tega lahko ugotovimo, da so dejanske razmere na sami površini kompozita C/C-SiC zaradi slabe toplotne prevodnosti še bolj neugodne kakor kažejo izmerjeni rezultati pod površino. To pomeni, da je glede na dobljene rezultate, pri razvoju ploščic za kompozitne diske C/C-SiC treba upoštevati dotikalne temperature precej višje od 550 °C. S tem pa se izbira materialov, ki zmorejo delovati pri tako visokih, četudi samo kratkotrajnih termičnih obremenitvah, bistveno zoži.

Dobljeni rezultati in ugotovitve o temperaturnih stanjih in vplivih toplotnih lastnosti analiziranih dvojic materialov pomenijo prvi korak raziskav pri optimiranju materiala ploščic za diske iz kompozitov C/C-SiC. Ugotovitve so še posebej pomembne, saj nakazujejo na dotikalne temperature precej prek 550 °C, kar bistveno oži izbiro materialov, hkrati pa nas dobro usmerja v iskanje primernih rešitev. Izmerjene vrednosti so zelo pomembne tudi za nadaljnje razumevanje dogajanja na zavornih

(Figure 3), even for short braking cycles during standard tests, which is because of the high frictional heat accumulation in the surface layer and the consequent high surface-temperature gradients. In the case of longer braking cycles and higher loads, for which the C/C-SiC composites are designed, the temperatures would reach even higher values. This can be anticipated from the results of the model tests (Figure 6) – purposely simulated for such conditions. After the first three braking cycles (25 seconds) in the contact with C/C-SiC the temperature already reached 550°C, Figure 5. Therefore, we can conclude that under these severe operating conditions the danger of overheating is substantial for C/C-SiC composite discs, and much higher than for steel discs. Moreover, although higher temperatures were reached in the model tests than in the standard tests, the temperature rise in steel discs was again gradual and much slower than would be anticipated in a realistic braking system. In the same time, i.e., after 3 braking cycles (25 seconds), the temperature reached only 250°C (Figure 6), which is 300°C less than in the case of the C/C-SiC composite brake disc, Figure 5.

An additional indicator of high expected temperatures in the contact with the C/C-SiC composite discs is the fact that on the model testing machine the temperature measurements were taken approximately 300-μm below the contact surface, which is relatively close to the heat source. However, it is known that the temperature rise on the surface is considerably higher than below the surface (due to frictional heat generation on the surface) and that the temperature can decrease by several hundreds of °C over the first 10 to 100 μm ([23] to [25]). Furthermore, due to the physical limitations of the temperature sensors, the “contact“ temperature measurement beneath the surface (or outside of the contact on the surface), shows lower values than reality ([26] to [30]). From the above it can be concluded that the actual surface conditions of the C/C-SiC composite are due to low thermal conductivity, and they are even more unfavourable than is suggested by the results from the measurement beneath the surface. This suggests that temperatures well above 550°C should be considered in the development of brake-pad material for use in C/C-SiC composite brake discs. This means that the choice of possible materials that can operate at these temperatures, even for short periods, is very small.

The presented results and findings about the surface-temperature conditions and the influence of the thermal properties of the analysed friction-couple materials represent the first step in the research and development of brake-pad materials for use in combination with C/C-SiC composite brake discs. These findings are of great importance since they indicate that contact temperatures well above 550°C can be expected in such braking systems, which substantially reduces the selection of pad materials; but at the same time directs us quite precisely to possible materials that will provide a solution. The temperatures that were identified in this study are also very important površinah, glede vpliva temperaturnega stanja na nastanek površinskih plasti ter tribokemijskih postopkov ([25], [31] do [35]). Prav ti postopki, s katerimi se bomo ukvarjali v naslednji fazi razvoja zavor na podlagi diskov iz kompozitov C/C-SiC, imajo ključno vlogo pri zagotavljanju ustreznega koeficienta trenja, obrabe ter dinamičnih lastnosti obravnavanega tribološkega sistema ([3], [5] in [6]), s tem učinkovitosti in kakovosti zavor.

4 SKLEPI

1. Rezultati na temelju uporabe dveh različnih preizkuševališč in načinov testiranja ter dveh načinov merjenja temperature kažejo enake sklepe o temperaturnih razmerah na površinah jeklenih in diskov C/C-SiC, in sicer, da so te razmere precej različne.
2. Temperaturni gradienti na zavornih površinah v dotikih s kompoziti C/C-SiC so znatno večji kakor pri jelenih diskih. Predvsem zaradi precej večje toplotne prevodnosti jekla od kompozita C/C-SiC, se ustvarjena torna toplota pri jeklenih diskih prevaja v notranjost v diska, pri diskih C/C-SiC pa se zadrži v precejšnji meri na površini.
3. Posledica takih toplotnih lastnosti so velike razlike v temperaturi na zavornih površinah: po nekaj zavornih ciklih na modelnem preizkuševališču so znašale kar 300 °C, v ustaljenih razmerah pa približno 200 °C.
4. Najvišje izmerjene temperature v dotikih s kompozitnimi diski C/C-SiC so po nekaj kratkotrajnih zavornih ciklih presegle 550 °C. Glede na velike padce temperatur tik pod površino, ocenjujemo, da je dejanska dotikalna temperatura v takih razmerah še za nekaj 100 °C višja.
5. Ugotovljene temperaturne razlike na zavornih površinah potrjujejo potrebo po izbiri drugačnih materialov od uporabljenih v navadnih zavornih sistemih ter na precej ožji izbor ustreznih materialov za zavorne ploščice, ki bodo zmožni delovati pri tako izrednih temperaturah.

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for further understanding the behaviour of contact surfaces in terms of the influence of temperature on the formation of surface layers, various tribo-films and tribochemical processes ([25], [31] to [35]). These processes will be the main subject in our further development of the C/C-SiC composite brake systems, since they have a major influence on the coefficient of friction, the wear and the dynamic characteristics of the discussed tribological system ([3], [5] and [6]), and thus on the efficiency and the quality of the whole braking system.

4 CONCLUSIONS

1. The results from two different testing machines and testing procedures and two different temperature-measurement methods suggest the same conclusions about the temperature on the surface of C/C-SiC composite and steel discs: there are significant differences in the evolution of the contact temperatures and their maximum values.
2. The temperature gradients in the contacts with C/C-SiC composite brake discs are significantly higher than with steel discs. This is mainly because of the much higher thermal conductivity of steel compared to C/C-SiC. Therefore, in contacts with steel discs the frictional heat is conducted into the bulk, whereas with the C/C-SiC discs the heat is to a large accumulated in the SiC surface layer.
3. The consequences of such thermal properties are the big differences in the surface temperatures of the steel and C/C-SiC discs. By using a model testing machine the obtained difference after a few brake cycles was 300°C, and under stationary conditions approximately 200°C.
4. The highest measured temperatures in the contact with C/C-SiC discs exceeded 550°C after a couple of short braking cycles. According to the high-temperature gradient beneath the surface, it is estimated that the actual contact temperature could be even several 100°C higher.
5. The identified temperature differences on the friction surfaces confirm the necessity of choosing different materials for C/C-SiC discs than those used in conventional brake systems. The temperature differences also suggest a much narrower choice of possible materials for brake pads that will be capable of operating under such extreme conditions.

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