Polish Society of
Composite Materials

Polskie Towarzystwo
Materiałów Kompozytowych

20: 2 (2020) 60-66

COMPOSITES
THEORY AND
PRACTICE

ISSN: 2084-6096
ISSN (online): 2299-128X

Paweł Szymański[1]*, Dorota Czarnecka-Komorowska[1], Katarzyna Gawdzińska[2]
Aleksandra Trubas[3], Ewelina Kostecka[2]

[1] Poznan University of Technology, Faculty of Mechanical Engineering, Institute of Materials Technology, pl. M. Sklodowska-Curie 5, 60-965 Poznan, Poland
[2] Maritime University of Szczecin, Department of Machines Construction and Materials, ul. Willowa 2-4, 71-650 Szczecin, Poland
[3] AGH – University of Science and Technology, Faculty of Non-Ferrous Metals, al. A. Mickiewicza 30, 30-059 Kraków, Poland
**Corresponding author. E-mail: pawel.szymanski@put.poznan.pl*

Received (Otrzymano) 15.04.2020

A REVIEW OF COMPOSITE MATERIALS USED IN BRAKE DISC PAD MANUFACTURING PROCESS

This article presents the conditions and factors influencing the performance and requirements of brake disc materials. The wear resistance of brake discs must be as high as possible since the reliability of brakes is a fundamental factor affecting the safety of the object in motion. The influence of temperature on the materials was also analyzed, and materials were selected for brake disc components. This article is a research and review study. The article describes studies performed on a flat single disc brake. The authors presented the abrasive wear rate for the tested composites (AlSi12/carbon and AlSi12/aluminosilicates) before and after heat treatment (solution heat treatment at 520°C/4 h and aging at 220°C/4 h). Abrasive wear resistance tests were carried out using a TRN S/N 18-324 device from CSM Instruments, combined with the TriboX v.2.96 system according to the description from the US in the ASTM G 99-90 standard.

Keywords: brake discs, working conditions, material selection, metal-polymer composites

PRZEGLĄD MATERIAŁÓW KOMPOZYTOWYCH STOSOWANYCH W PROCESIE WYTWARZANIA TARCZ HAMULCOWYCH

Przedstawiono warunki i czynniki wpływające na działanie oraz wymagania dotyczące materiałów tarcz hamulcowych. Odporność na zużycie tarcz hamulcowych musi być jak najwyższa, ponieważ niezawodność hamulców jest podstawowym czynnikiem wpływającym na bezpieczeństwo poruszającego się obiektu. Przeanalizowano także wpływ temperatury na MMC i zaprezentowano materiały na elementy tarczy hamulcowej. Artykuł ten ma charakter przeglądowy. Opisano w nim jedynie badania autorów przedstawiające wskaźnik zużycia ściernego dla metalowych materiałów kompozytowych (AlSi12/węgiel i AlSi12/glinokrzemian) przed i po obróbce cieplnej (obróbka cieplna wygrzewanie w temperaturze 520°C/4 godziny i starzenie w temperaturze 220°C/4 godziny). Testy odporności na zużycie ścierne wykonano z użyciem urządzenia TRN S/N 18-324, CSM Instruments, w połączeniu z systemem TriboX v.2.96 zgodnie z normą ASTM G 99-90.

Słowa kluczowe: tarcze hamulcowe, warunki pracy, dobór materiałów, kompozyty metalowo-polimerowe

INTRODUCTION

The multitude of materials currently available makes it necessary to choose the proper ones for structural or functional elements, tools, as well as other products or their parts. This choice should be based on multi-criteria optimization, which takes into account the properties of these materials. The materials used for the friction components in brake pads – discs and pads – should be characterized by [1-20]:

- high and stable coefficients of friction, regardless of the operating conditions,
- high resistance to wear and tear in a wide range of working conditions,
- high resistance to high temperatures,
- high mechanical resistance,
- resistance to wear and tear by abrasive surfaces and ease of run-in,
- low hygroscopicity.

This can be seen when a machine is being built which is supposed to be as reliable as possible, in particular when it comes to the safety of the people and goods it transports, e.g. brake discs in jet aircraft (graphite and carbon composites). These brakes must brake an aircraft landing from a very high speed over a relatively short distance and, simultaneously, withstand the temperature generated by the friction of the brake pair, which can reach 2000°C [4-18]. These discs do not lose their thickness during operation in contrast to their classical cast-iron equivalents. The progressive wear of a disc is determined by the mass, and the second very important advantage is their weight. The unit weight of such a disc can be 50÷70% lower than that of its cast iron equivalent, and they are also much more resistant to high temperatures. This means that in practice if the brake pads are damaged, the discs will not overheat. Unfortunately, these discs are still expensive [10-16, 23-31].

Currently, the designer's experience and intuition, and even his or her own habits, are very important factors in selecting materials for specific applications. Nowadays, within the framework of computer-aided design (CAD) and manufacturing (CAM) systems, there is also room for the use of these computer-aided systems to select materials [4, 5, 7, 8, 14, 17, 18]. This eliminates many factors and subjective errors, and it ensures that the selected materials have the most advantageous usage and technological properties such as appropriate densities as well as the lowest possible material and production costs. The use of computer methods requires the development of extensive databases containing information about numerous materials and their properties [8, 32]. The essential step in determining the selection criteria for materials are the working conditions, for which it is necessary to determine the material requirements for the construction of a specific part.

This article addresses brake discs because the working conditions of a disc have a number of requirements for the material used in its production, which limits the possible designs. However, these working conditions offer some possibilities for further development of brake discs in order to achieve greater braking efficiency. The disc is an essential part of the brake, and several important criteria must be considered during its design. For example, its dimensions must enable the maximum amount of energy to be transmitted during braking, and its wear resistance must be as high as possible since the reliability of the brakes is a fundamental factor in driving safety [4, 7, 14-18, 33-35]. Thus, it is highly important to determine the criteria for the selection of materials used in brake friction discs.

The main feature that distinguishes axial and radial brake mechanisms are the different directions of forces between the friction surfaces. In the last dozen or so years, disc brakes have been widely implemented due to their many advantages. There are three main types of disc brake: a conical single disc brake, a flat single disc brake (Fig. 1), and a flat multiple disc brake.

The ever-expanding use of disk brakes stems from their many advantages, including:

- operation of the disc brake does not depend on the movement direction,
- the forces pressing the brake pads do not cause additional load on the brake linings or rolling bearings,
- the equilibrium between the pressing forces exerted on the pads by the shaft ring, either as a full cross-section disc or with ventilation ducts, does not affect the geometric shape of the shaft ring,
- the ability to maintain the same clearance between the shaft and the lining over the entire surface minimizes the brake stroke,
- the manufacture of a properly rigid block, and its surface processing are technically easy,
- the wear of the lining is evenly distributed over the entire friction surface,
- the cooling intensity of the system is increased due to the exposure of a large surface area of the disc, as well as its ventilation properties,
- flat brake components are less sensitive to thermal deformation.

Fig. 1. View of a brake disc

Rys. 1. Widok hamulca tarczowego

WORKING CONDITIONS AND REQUIREMENTS OF BRAKE DISC PADS

The conditions under which braking systems operate, similar to power transmission systems, are extremely difficult. Variable dynamic loads caused by braking with varying degrees of intensity adversely affect the components, especially those related to the braking mechanisms, causing significant damage to the friction surface. The specificity of the braking system operating conditions also applies to high operating temperatures during sudden braking and the influence of water, dust, and mud in adverse weather and terrain conditions, which can change the coefficient of friction between the cooperating friction elements. It is important to ensure that the essential braking components, especially the friction components, experience as little wear as possible during service. Additionally, the entire braking system should require as little maintenance and adjustment during operation as possible. Brake designs are currently being developed to rapidly dissipate significant amounts of heat which occur during brake operation and to reduce fluctuations in the coefficient of friction between the cooperating friction mechanism elements [21-23, 27, 30, 31]. The operating conditions of braking systems impose a number of requirements such as:

- developing sufficiently high braking forces to enable the tire to take full advantage of its adhesion to the road on a variety of surfaces,
- independence of the degree of utilizing adhesion from the loading conditions of a vehicle working independently and as part of a road set,
- performance in all road conditions and load variations,
- work proportional to wheel loads, ensuring stability of the braking movement of the vehicle regardless of the road surface condition,
- minimum delay in applying and releasing the brakes,
- effective protection in the event of a braking system failure,
- high durability and reliable operation,
- easy start-up and operation.

In most cases, the actual contact surface of technical friction pairs, like friction brakes, are a minimal part of the nominal surface of the friction elements. They are the sum of the elementary fields of the contact surfaces, which are temporary in nature and are not evenly distributed over the nominal contact surface. Regardless of the size, quantity, and distribution of the elementary contact surfaces, friction occurs during the relative movement of the friction elements in the contact surfaces and their surroundings. In the same micro-areas of each friction element, friction has both thermal and mechanical effects, e.g. wear, heat generation, and surface layer deformation. In friction systems which experience high relative motion speeds, such as friction brakes, thermal and mechanical contact phenomena have a dominant influence on the tribological characteristics [1, 3, 27-29, 32, 34].

The magnitude of dry friction forces is influenced by two types of interactions: the interaction of adhesive bonds between the contacting surfaces, and the deformation resistance of materials in micro-areas of contact. The first component of the frictional forces depends on the compatibility of the friction pair as well as the physical and chemical purity of the surface of these elements. The second component is the plastic deformation resistance of the tribological system elements during their mutual movement and includes furrowing of the softer material through the tips of the micro-irregularities of the hard material, plastic deformation, and crushing of the third body. A large portion of the friction energy is significantly dissipated by plastic deformation of the surface layer and can be observed during the testing of friction machine samples [8, 31]. In general, this type of microsection reveals the existence of a strongly deformed amorphous layer, partly composed of applied third body particles between 2 and 30 μm thick. The next layer, 100 to 200 μm below it, usually retains its original crystalline structure but exhibits a targeted plastic grain deformation. About 95% of the friction energy is converted into thermal energy through plastic deformation of the outer layers – in which both friction pair elements are only about 5 μm thick – and through deformation of the third body (Fig. 2). The temperature increase of the rubbing bodies is mainly due to the transformation of friction energy into thermal energy, which first occurs in the elementary contact areas and their surroundings [8, 21-23, 27, 29-31]. Temperature has an important influence on the tribological characteristics, durability, and reliability, therefore a great deal of theoretical and experimental research has been conducted to develop methods to determine and predict friction surface temperatures, temperature gradients, and associated thermal stresses [5, 7, 28, 32-34, 36].

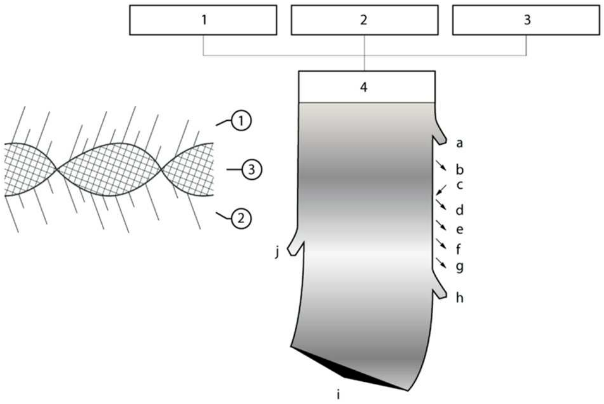

Fig. 2. Transformation of friction energy, with: 1, 2 – friction pair elements, 3 – third body, 4 – friction energy, a – surface energy, b – energy of secondary processes, c – tribo-chemical reactions, d – structural transformations, e – tribo-emission, f – tribo-luminescence, g – tribo-sublimation, h – mechanical vibrations and noise, i – heat, j – stored deformation energy (based on [4, 6, 27])

Rys. 2. Transformacja energii tarcia za pomocą: 1, 2 – elementów pary ciernej, 3 – ciała trzeciego, 4 – energii tarcia, a – energii powierzchniowej, b – energii procesów wtórnych, c – reakcji tribochemicznych, d – przekształceń strukturalnych, e – triboemisja, f – triboluminescencja, g – tribosublimacja, h – wibracje mechaniczne i hałas, i – ciepło, j – zmagazynowana energia deformacji (na podstawie [4, 6, 27])

The heat generated by the brakes and the temperature increase cause thermo-elastic deformation of the friction parts [8, 31], which increases local individual pressure variations between these elements. This creates a closed chain of unstable causes and effect events in which local pressure increases are accompanied by more intense local heat generation, increased temperature, additional deformation of the friction pair components, and further increases in the individual pressure differentiations. This phenomenon is called thermo-elastic instability. It has been shown that localized temperature increases caused by the thermo-elastic instability of a friction brake may cause: accelerated degradation of the friction material, the formation of thermal fatigue cracks on the surfaces of the friction elements, and periodic reduction of the braking torque.

MATERIAL SELECTION AND MACHINING

The design features and operating conditions of friction brakes in working machines and vehicles are very diverse, and current solutions place an increased mechanical load on the friction pair components. To describe the mechanical properties of brake discs, it is necessary to determine the elasticity modulus, fatigue strength, material malleability, and fatigue index. Diversification of the operational parameters of friction brakes has forced the development of a very wide range of specialized friction materials designed for the friction elements of these assemblies. To describe frictional phenomena with respect to thermal phenomena, the following values should be used when evaluating the brake disc materials: thermal conductivity, diffusivity, specific heat, melting point, glass transition temperature, coefficient of thermal expansion, thermal surge resistance, and creep resistance. These properties must be applied equally to at least two brake components of the tribological pair, namely the roller ring (disc, drum, etc.) and the friction component (lining, cap, pad, etc.). The most common material used in the roller ring of automotive friction brakes is a fine-grained perlite lamellar cast iron matrix with a hardness from 180 to 240 HV and reinforced magnesium-silicon aluminum alloys with a hardness of 120 HV. For friction speeds above 25 m/s, cold-rolled or forged carbon steel alloy or cast iron and spheroidal cast iron are recommended because after heat treatment it reaches a hardness of about 370 HB. Stainless steels are good solutions only when the corrosive wear of carbon steels is a significant problem. For specific applications where the initial braking speed exceeds 100 m/s, e.g. in express trains or airplanes, fabricating carbon steel discs coated with ceramic or plasma sprayed cermets is proposed [9-20, 28-30, 32, 34]. The purpose of this double-layered coating is to:

a) limit heat transfer in the direction of the axes and bearings (the internal insulation coatings have thicknesses of approx. 400 μm and the composition of NiCrAlY-ZrO_2),
b) improve the wear resistance (the outer layer is approx. 250 μm thick, with a hardness of 800 HV and the composition of Cr_3C_2-NiCr [8, 31]).

Different criteria can be used to classify friction materials. The most general division distinguishes three material groups:

a) non-metallic, which includes:
   - cotton or asbestos-free with an organic bonding agent,
   - organic (e.g., wood, leather, felt, bentonite, and others),
   - inorganic (e.g., ceramic, cermets, graphite-carbon, and others),
   - materials pressed with a mixed binding agent, woven, and impregnated with drying oils,
   - materials pressed with a thermosetting resin bonding agent,
b) metals, including grey and phosphorus cast iron, low carbon steels, metal sinters (FeCu), certain copper alloys, and others,
c) composites, e.g. metal-resin composites, where the three main components are thermosetting resin (phenolic resin, polyimide resin, cyanate ester resin, polyurethane rubber, phenolic resin, and phenolic-formaldehyde), fillers such as a fibrous component (glass fibers, silica fibers, carbon fibers, aramid fibers, sisal, and coconut fibers, and steel fibers) [37, 38] and metal powders in quantities ranging from 20 to 70 wt.%, or metal powders, commonly with an aluminum matrix (Tables 2 and 3).

Phenolic resin is currently the most common resin binder used in brake friction materials due to good mechanical properties, for example, compressive strength, high hardness, creep resistance, good wetting capability and it is cheap to produce. Phenolic resin and phenol-formaldehyde resin are resistant to high temperature, approx. 300°C, in the case of severe braking conditions. At that temperature, the phenolic resin undergoes thermal degradation of the methylene and phenol groups, which significantly increases the wear of the brake pads increased [37, 39, 40]. Therefore, these resins are chemically modified using phenol- and alkyl ether, alkyl benzene, cashew-nut-shell liquid, nitrile-butadiene rubber. It can provide a polymer lining with greater tribological properties [41]. The selected composition of composites used for brake pad manufacturing is presented in Table 1 [39, 41, 42].

TABLE 1. **Composition of selected metal-polymer resin composites used for brake pad manufacturing**

TABELA 1. **Skład wybranego kompozytu metalowo-polimerowego stosowanego do wytwarzania tarcz hamulcowych**

Resin	Components	Properties
Phenolic resin (7%)	63% friction modifiers (graphite, tin sulfide, zinc sulfide, aluminum), 23% steel fibers and chips, 7% vermiculite [39]	thermal stability to 300°C (COF = 0.4)
Phenolic resin (16%)	5% Kevlar, 26% wollastonite, 16% $BaSO_4$, 15% friction particles (CNSL), 16% dolomite [41]	excellent friction, good thermal stability to 300°C
Phenolic resin (40%)	13% titanium oxide, 10% silicon carbide, 2% zirconium oxide, 4% graphite, 10% aluminum, 6% hexamethylenetetramine, 15% coconut fiber [42]	stabile coefficient of friction (COF = 0.26) good thermal stability to 300°C

The metal-polymer composites are characterized by advantageous friction-wear properties compared with non-metallic materials, including a stable coefficient of friction at elevated temperatures, higher permissible unit pressure, and greater resistance to wear [8, 9, 11-14, 17-21, 43]. The authors presented the abrasive wear rate for the tested MMC composites (AlSi12/carbon and AlSi12/aluminosilicates) before and after heat treatment (solution heat treatment at 520°C/4 h and aging at 220°C/4 h). The matrix of the composites used in this study was an aluminum alloy (AlSi12), with reinforcement – preforms from unordered short fibers – in one case: carbon in the form of graphite, in the other case: aluminosilicate.

Abrasive wear resistance tests were conducted using a TRN S/N 18-324 device from CSM Instruments, combined with the TriboX v.2.96 system. The method was chosen because it is well documented in the professional literature and recognized as a recommended method for comparative tests of tribological properties of materials. The method, described in the US in the ASTM G 99-90 standard, at present has no equivalent in Polish or WEU standards. Balls with a 6 mm diameter made of aluminum oxide were used as the counter samples. The pressure of the counter samples was selected by a special program, Model X, a component of the above-mentioned system. The selected load was 1 N. The friction distance of 200 m and linear speed of 3 cm/s were adopted. The tests were carried out using reciprocal motion. The tribotester recorded the coefficient of friction and wear depth in time (and as a function of friction distance). The abrasive wear rate for the composites before and after heat treatment (solution heat treatment at 520°C/4 h and aging at 220°C/4 h) is given in Figure 3. The wear rate was determined from the formula (1)-(2) [21]:

$$K = \frac{V}{F \cdot S} \tag{1}$$

where: K is the wear rate $\left[\frac{\mu m^3}{N \cdot m}\right]$; F is pressure [N]; S is the friction distance [m]; V is the total volume loss [μm^3]

$$V = V_S + V_{cs} \tag{2}$$

where V_S is the volume loss in a sample [μm^3], V_{cs} is the volume loss in the counter sample [μm^3] [21].

It follows from Figure 3 that the AlSi12/aluminosilicate composite before thermal treatment has the lowest resistance to abrasive wear. It is known that the phase precipitation from a supersaturated solid solution in silumin is attained by annealing at a temperature at which the equilibrium structure is a 'pure' solid solution, then cooling the material to a temperature at which the solid solution is metastable, and the mixture of the two phases is a stable structure [1, 21, 43]. The abrasive wear of AlSi12/carbon is the lowest (Fig. 3). This is presumably connected with the presence of carbon in the composite as the reinforcement phase. The lubricating properties of this material are commonly known [6, 43, 44].

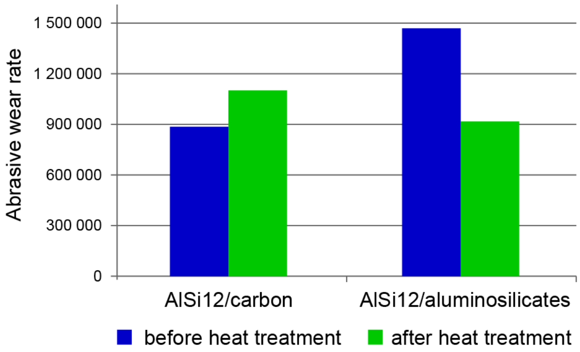

Fig. 3. Abrasive wear rate of tested materials before and after heat treatment (heat treatment at 520°C/4 h and aging at 220°C/4 h) [authors' own research]

Rys. 3. Wskaźnik zużycia ściernego badanych materiałów przed i po obróbce cieplnej (obróbka cieplna w temperaturze w 520°C/4 godz. i starzenie w 220°C/4 godz.) [badania własne]

When selecting a brake disc material, it is also necessary to examine the resistance to mechanical wear and tear caused by corrosive processes as well as to evaluate the impact of machining on this wear and tear [1, 13, 17, 27, 31, 33]. Table 2 summarizes the distribution of friction materials combined with an approximate numerical evaluation of the main performance and operating parameters (coefficient of friction, unit pressure, permissible operating temperature, and maximum speeds). Table 2 also presents the use of different types of braking systems in various means of transport and in industrial machinery.

Table 3 shows the selected properties of other composite materials used or likely to be used as brake discs for traditional cast iron discs. The table shows that the composite materials are light, and they have much better properties than gray cast-iron with flake graphite.

TABLE 2. **Characteristics of friction materials in brake systems (based on [5-8, 23, 34])**

TABELA 2. **Charakterystyka materiałów ciernych stosowanych na układy hamulcowe (na podstawie [5-8, 23, 34])**

No.	Friction materials	Dry coefficient of friction [μ]	Max. single pressure [MPa]	Max. temperature		Max. speed [m/s]	Use in brakes
				Temporary [°C]	Permanent [°C]		
1	Cermet sinters (e.g. CrC-NiCr)	0.3	1.0	850	450	> 50	Disc: trains, airplanes
2	Ceramic sinters (e.g. Al-TiO)	0.4	3.0	1500	550	> 50	Disc: high-speed, trains, airplanes
3	Metal sinters (e.g.Cu-Fe)	0.29÷0.32	2÷2.8	500÷550	300÷350	> 50	Disc: trains, airplanes
4	Metal (e.g. Al, Mg, Ti) carbon composites	0.15÷0.4	3	2000	–	> 60	Multiple discs: jets
5	Resin-ceramic pressed	0.35÷0.4	0.7÷5	500÷700	200÷300	0	Disc and drum: cars, cranes
6	Woven ceramic-resin	0.38	0.7	150	125	18	Radial: industrial machinery
7	Woven cotton-resin	0.47	0.7	110	75	18	Radial: industrial machinery
8	Cast iron-steel	0.15÷0.2	1.0	320	1200	20	Radial: rail vehicles

TABLE 3. **Selected properties of metal composite brake discs [8]**
TABELA 3. **Wybrane właściwości tarcz hamulcowych z kompozytów metalowych [8]**

Matrix alloy	(Al-Si)	(Al-Zn)	(Al-Zn)	(Al-Si)	Gray cast iron with flake graphite
Reinforcing phase	SiC	Al_2O_3	Al_2O_3	SiC	–
Volumetric share of reinforcing phase [%]	30	25	38	20	–
Method of manufacturing	Casting into sand moulds	Casting into sand moulds	Pre-form technology (infiltration)	Permanent mold casting	Casting into sand moulds
Density [g/cm^3]	2.89	2.80	2.88	2.77	6.9÷7.4
Tensile strength [MPa]	225	180	220	220	100÷400
Young's module [GPa]	127	100	137	100	80÷150
Coefficient of thermal expansion [μm/mK]	14.8	18.0	14.5	17.5	9.0÷11.0
Thermal conductivity [W/mK]	156	130	95	150	50
Specific heat [J/kg·K]	820	830	830	820	460÷840
Maximum operating temperature [°C]	480	480	540	300	800

The materials used for brake discs must meet the criteria given in Table 4.

TABLE 4. **Material properties as selection criteria for brake discs**
TABELA 4. **Kryteria wyboru materiału stosowanego na tarcze hamulcowe pod względem właściwości**

Properties	Determining factor
Economical	Cost corresponds to quality of product
Mechanical	Elastic strength modulus Ductility Fatigue indicator
Thermal	Thermal conductivity diffusivity Specific heat Melting point Glass transition temperature Thermal expansion coefficient Thermal surge resistance, creep resistance
Wear (including corrosive wear)	Wear indicator, corrosive wear assessment

CONCLUSIONS

In many cases, the primary selection criterion is the relative cost of the product, and even if the selected material does not fully meet all the requirements, it is used because the cost of a better material is too high. The best solution for a wide range of design possibilities would require an unlimited budget.

The material choice for brake discs in the automotive industry gives the designer some room to maneuver, and there are no rigid criteria here such as those in the aircraft industry. Therefore, in order to reduce the production costs of a new car, automobile manufacturers use inferior materials and offer better quality parts for after-sales service.

REFERENCES

[1] Sika R., Rogalewicz M., Popielarski P., Czarnecka-Komorowska D., Przestacki D., Gawdzińska K., Szymański P. Decision support system in the field of defects assessment in the metal matrix composites castings, Materials 2020, 13, 3552-3578.

[2] Krawczyk J., Pacyna J., Effect of the cooling rate on the mottled cast iron microstructure designed for the mill rolls, Metallurgy and Foundry Engineering of Science and Technology 2009, 35, 101-110.

[3] Mercado-Solis R.D., Talamantes-Silva J., Beynon J.H., Hernandez-Rodriguez M.A.L, Modelling surface thermal damage to hot mill rolls, Wear 2007, 263, 1560-1567.

[4] Michalczuk H., Tubielewicz K., Chmielik I.P., In preparation control code lathes CNC, Mechanik 2014, 87, 7, 413-422.

[5] Mucha M., Nowoczesne technologie wykonywania cylindrycznych powierzchni (tarczowe), Master thesis, Częstochowa 2008.

[6] Popczyński K., Określenie i uzasadnienie kryteriów doboru materiałów i technologii w produkcji wybranego podzespołu, Praca przejściowa napisana pod kierunkiem W. Przetakiewicz, WAT, Warszawa 2010 (niepublikowane).

[7] Tubielewicz K., Michalczuk H., Chmielik I.P., Brake disc technology, Mechanik 2015, 7, 885-894.

[8] Wojciechowski A., Sobczak J., Kompozytowe tarcze hamulcowe pojazdów drogowych, Instytut Transportu Samochodowego, Warszawa 2001.

[9] Basavarajappa S., Chandramohan G., Mukund K., Ashwin M., Prabu M., Dry sliding wear behavior of Al 2219/SiCp-Gr hybrid metal matrix composites., Journal of Materials Engineering and Performance 2006, 15(6), 668-674.

[10] Mondal A.K., Kumar S., Dry sliding wear behavior of magnesium alloy based hybrid composites in the longitudinal direction, Wear 2009, 267, 458-466.

[11] Vencl A., Rac A., Bobic I., Tribological behaviour of Al-based MMCs and their application in automotive industry, Tribol. Industry 2004, 26(3-4), 31-38.

[12] Srivastava S., Mohan S., Study of wear and friction of Al-Fe metal matrix composite produced by liquid metallurgical method, Tribol. Industry 2011, 33(3), 128-137.

[13] Kumar K.R., Mohanasundaram M.K., Arumaikkannu G., Subramanian R., Effect of particle size on mechanical properties and tribological behaviour of aluminium/fly ash composites, Science and Engineering of Composite Materials 2012, 19(3), 247-253, DOI: 10.1515/secm-2011-0139.

[14] Naplocha K., Granat K., Dry sliding wear of Al/Saffil/C hybrid metal matrix composites, Wear 2008 265, 1734-1740.

[15] Ramesh C.S., Adarsha H., Pramod S., Khan Z., Tribological characteristics of innovative Al6061-carbon fiber rod metal matrix composites, Mater. Design 2013, 50, 597-605.

[16] Uyyuru K.R., Surappa K.M., Brusethaug S., Tribological behavior of Al-Si-SiCp composites/automobile brake pad system under dry sliding conditions, Tribology International 2007, 40, 365-373.

[17] Majhi S., Samantarai P.S., Acharya K.S., Tribological behavior of modified rice husk filled epoxy composite, International Journal of Scientific & Engineering Research 2012, 3, 6, June.

[18] Deshmanya B., Purohit K.G., Development of mathematical model to predict micro-hardness of Al7075/Al2O3 composites produced by stir-casting, Journal of Engineering Science and Technology Review 2012, 5, 1, 44-50.

[19] Popielarski P., Hajkowski J., Sika R., Ignaszak Z., Computer simulation of cast iron flow in castability trials, Archives of Metallurgy and Materials 2019, 64, 4, 1433--1439, DOI: 10.24425/amm.2019.130110.

[20] Popielarski P., Ignaszak Z., Effective modelling of phenomena in over-moisture zone existing in porous sand mould subjected to thermal shock, drying and energy technologies, Advanced Structured Materials 2016, 63, 181-206, DOI: 10.1007/978-3-319-19767-8_10.

[21] Gawdzińska K., Bryll K., Nagolska D., Influence of heat treatment on abrasive wear resistance of silumin matrix composite castings, Archives of Metallurgy and Materials 2016, 61(1), 177-182.

[22] Gawdzińska K., Chybowski L., Przetakiewicz W., Study of thermal properties of cast metal-ceramic composite foams, Archives of Foundry Engineering 2017, 17(4), 47-50.

[23] Gazda A., Homa M., Determination of thermal conductivity of selected types of ductile iron (spheroidal graphite/cast iron) by means of thermal diffusivity measurements with laser-flash method, Prace Instytutu Odlewnictwa 2009, 2, 5-18.

[24] Ribeiroa L., Barbosab A., Vianaa F., Monteiro Baptistac A., Diasd C., Ribeiroa C.A., Abrasion wear behaviour of alloyed and chilled cast irons, Wear 2011, 270, 535-540.

[25] Krawczyk J., Pacyna J., Influence of a matrix on properties of mottled cast iron applied for mill rolls, Archives of Foundry Engineering 2010, 10, 45-50.

[26] Coronadoa J.J., Gómeza A., Sinatoraa A., Tempering temperature effects on abrasive wear of mottled cast iron, Wear 2009, 267, 2070-2076.

[27] Madej W., Gazda A., Badanie termofizycznych właściwości wysokofosforowego żeliwa P30 stosowanego na nowego typu wstawki hamulcowe dla kolejnictwa, Odlewnictwo Współczesne – Polska i Świat 2009, 4, 3-6.

[28] Orłowicz A.W., Mróz M., Tupaj M., Trytek A., Jacek M., Radoń, M., Cavitation erosion of nodular cast iron – microstructural effects, Archives of Foundry Engineering 2017, 17, 4, 119-122.

[29] Orłowicz A.W., Mróz M., Tupaj M., Trytek A., Kupiec B., Korzeniowski M., Sondej K., Kozak L., The effect of carbides orientation in NC11 steel on scratch susceptibility of die inserts used to press stampings for refractory shapes, Archives of Foundry Engineering 2016, 16, 2, 95-98.

[30] Przestacki D., Szymanski P., Wojciechowski S., Formation of surface layer in metal matrix composite A359/20SiCP during laser assisted turning, Composites Part A: Applied Science and Manufacturing 2016, 91, 1, 370-379.

[31] Wrzesiński T., Teoria samochodu. Hamowanie pojazdów samochodowych, WKiŁ, Warszawa 1978.

[32] Gawdzińska K., Nagolska D., Szymański P., Determination of duration and sequence of vacuum pressure saturation in infiltrated MMC castings, Archives of Foundry Engineering 2018, 18(1), 23-28.

[33] Bartkowska A., Pertek A., Popławski M., Bartkowski D., Przestacki D., Miklaszewski, A. Effect of laser modification of B-Ni complex layer on wear resistance and microhardness, Optics & Laser Technology 2015, 72, 116-124.

[34] Gawdzińska K., Chybowski L., Nabiałek M., Szymański P., A study of metal-ceramic composite foams combustibility, Acta Physica Polonica A 2019, 135(2), 304-307.

[35] Nozdrzykowski K., Chybowski L., A force-sensor-based method to eliminate deformation of large crankshafts during measurements of their geometric condition, Sensors 2019, 19(16), 3507, 1-25.

[36] Krawiec P., Różański L., Czarnecka-Komorowska D., Warguła Ł., Evaluation of the thermal stability and surface characteristics of thermoplastic polyurethane V-belt, Materials 2020, 13, 1502.

[37] Xin, Cheng Guang Xu, Liu Fei Qing, Friction properties of sisal fiber reinforced resin brake composites, Wear 2007, 4, 4262, 5-6, 4, 736-741, DOI: 10.1016/j.wear.2006.08.010.

[38] Czarnecka-Komorowska D., Grześkowiak K., Popielarski P., Barczewski, M., Gawdzińska K., Popławski M., Polyethylene wax modified by organoclay bentonite used in the lost-wax casting process: Processing – structure – property relationships, Materials 2020, 13, 2255.

[39] Menapace C., Leonardi M., Secchi M. et al., Thermal behavior of a phenolic resin for brake pad manufacturing, J. Therm. Anal. Calorim. 2019, 137, 759-766.

[40] Chen Y., Chen Z., Xiao S., Liu H., A novel thermal degradation mechanism of phenol-formaldehyde type resins, Thermochim. Acta 2008, 476(1-2), 39-43.

[41] Hai-Qing Wang, Xing-Yang Wu, Tong-Sheng Li, Xu-Jun Liu, Pei-Hong Cong, Effect of the matrix resin structure on the mechanical properties and braking performance of organic brake pads, Journal of Applied Polymer Science 2012, 126, 1746-1753.

[42] Crciun A.L., Pinca-Bretotean C., Birtok-Băneasă C., Josan A., Composites materials for friction and braking application, 2017 IOP Conf. Ser.: Mater. Sci. Eng. 2009, 200, 1, DOI: 10.1088/1757-899X/200/1/012009.

[43] Pietrowski S., Silumins, Lodz University of Technology, Lodz 2001 (in Polish).

[44] Fu H.H., Han K.S., Song J., Wear properties of Saffil/Al, Saffil/Al_2O_3/Al and Saffil/SiC/Al hybrid metal matrix composites, Wear 2004, 256, 705-713.