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MATERIAL INVESTIGATIONS OF COMPOSITES AND THEIR SELECTED APPLICATIONS IN MOTOR TRANSPORT

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Abstract

The paper presents advances in the range of brake discs and engine pistons production using metal matrix composites and identifies their advantages in comparison to materials traditionally applied. The wear characteristics in the case of brake discs and thermal shock resistance in the case of pistons were determined. The wear was assessed by measurements of friction coefficients in different temperatures. The thermal shock resistance was described as the crack length formed during the tests. The image analysis was used in the quantitative microstructure assessments for determination of synthetic geometrical parameter correlated with composites properties. The two synthetic geometrical variables have been proposed in the microstructure description of a new generation brake discs and pistons. The selected relationships between functional properties and composite microstructure are presented. It was shown that a life of brake discs made from A359 aluminum alloy reinforced by SiC precipitates is much longer in *comparison to traditional, made from cast iron. It was ascertained also that the best thermal shock resistance was obtained in the case of AK12 composite with Al_2O_3 short fibers in cast heat treated.*

The results may be treated as the base for the recommendations of tested metal matrix composites for applicability in selected vehicle parts and subsets producing.

Keywords: *metal matrix composites, microstructure, properties, applications*

1. Introduction

A dynamic development of different composite materials, including these of aluminum matrix base, is observed over the last decade. At present, their rapid development is regarded by many research centers as one of the most important tasks to be solved by means of the intensive investigations. A direct reason of such situation is connected with their attractive functional properties and width applicability, especially in the motor industry [1, 2, 3].

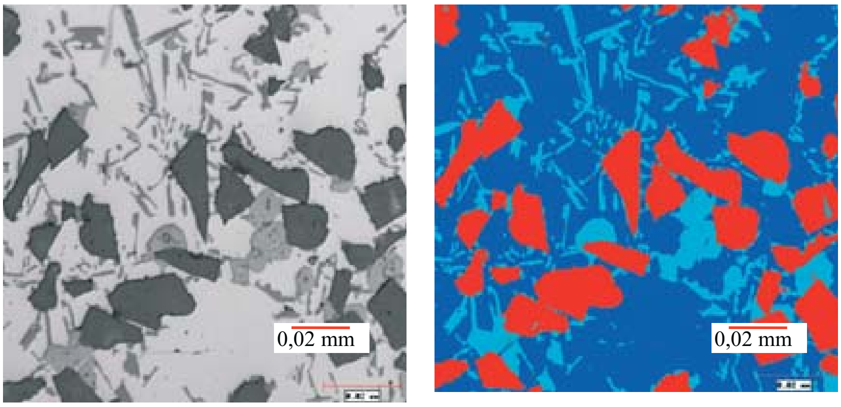
The main aims of the motor industry are related to minimization of the vehicle weight, fuel consumption and emission of exhaust gases. On the other hand, a regular development of the motor transport should fulfill several important requirements such as a facility and low cost production, a high standard of the product quality (as a consequence of the properties improvement due to the conscious material structure formation), a functional reliability, etc.

The worldwide basic applications of metal matrix composites in the motor transport are: some elements of driving gears (connecting shafts, slide bearings), engines (block of engines, pistons, connecting rods), braking systems (break discs and drums) and suspension systems. According to vehicle designers a density, monotonic loading and fatigue characteristics at room and elevated temperatures, stiffness, resistance to friction, and ability to the damping of vibrations are the most important properties of MMCs. All of them should be investigated in detail. Moreover, these tests should be associated with the metallographic observations on different levels.

The paper presents some examples of the quantitative metallographic assessments on the basis of microstructural investigations carried out using selected composite materials. The computer image analysis was applied in these assessments.

2. Quantitative relationships between the impact resistance and microstructure [4]

The composite material F3N.20S (DURALCAN-AlSi10.18Mg0.61Mn0.64Fe0.98 modified by Sr and dispersive reinforced by 21 Vol. % of SiC about 20 µm size) was applied in all tests. It was obtained by squeeze casting method (under 220 MPa pressure). The material was tested by means of pendulum hammer (Louis-Schopper) having initial impact energy equal to 6J (sample without notch). The composite microstructure is presented in Fig. 1.



a b

Fig. 1. Composite microstructure: a) real image, b) image prepared to quantitative microstructure analysis (SiC reinforcing phase-grey and Si eutecticlight-grey)

The synthetic geometrical microstructural parameter was proposed on the basis of results achieved. It can be expressed in the following way:

$$\xi = \sqrt{\frac{F_1 \times F_2}{N_{A1} \times N_{A2} \times V_{V2}}}\,, \tag{1}$$

where:

F_1 - average Feret diameter for reinforcing phase SiC [mm],
F_2 - average Feret diameter for eutectic Si [mm],
N_{A1} - average number of precipitates of reinforcing phase SiC [mm^{-2}],
N_{A2} - average number of precipitates of eutectic Si [mm^{-2}],
V_{V2} - volume fraction of precipitates of eutectic Si.

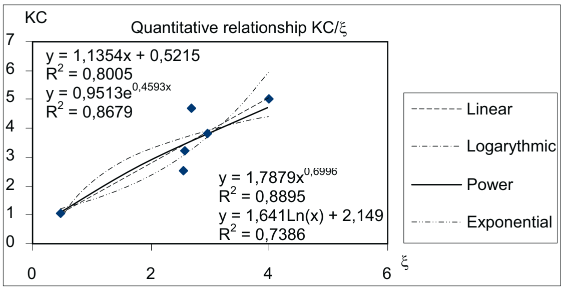
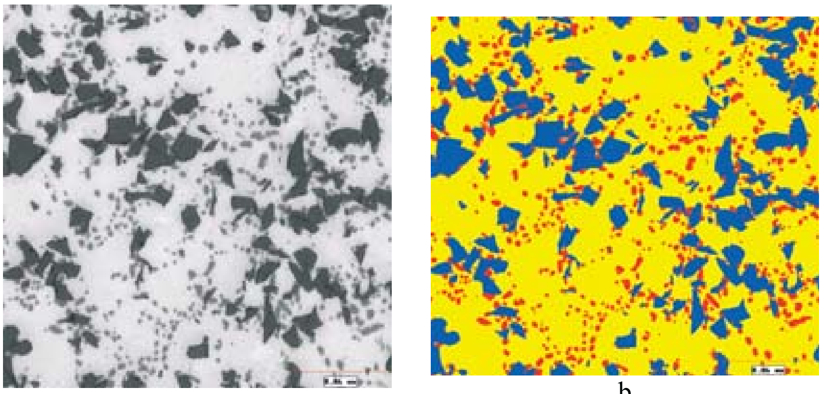


Fig. 2. Quantitative relationship between impact energy (KC) and synthetic geometrical parameter (ξ)

3. Quantitative relationships between the tensile strength and microstructure [5]

Two groups of composites based on aluminum alloy (A359) were tested before and after machining in order to determine a tensile strength. The microstructure of the composite is presented in Fig. 3.



a

b

Fig. 3. Microstructure of F3S.30S composite, magn. x200, a) real image, b) image prepared to quantitative microstructure analysis (SiC reinforcing phase-black and Si eutectic - grey)

The same geometrical parameters of the reinforcing phase (SiC precipitates) as those considered in Section 2 as well as of Si precipitates existing in the composite matrix were assessed by means of the image analysis.

It was possible to formulate the synthetic stereological variable in the form of $\chi=(N_A/F_{śr})^{1/2}$ concerning the reinforcing phase and correlated with the tensile strength (Tab. 1).

Tab. 1. Correlation coefficients (r) between tensile strength (R_m) and stereological parameter (χ) and their calculated (t_o) and theoretical (t_t) significances

Number of samples	Correlation coefficient - R_m/χ	Calculated significance - t_o	Theoretical significance - t_t
1-10	-0.46542	2.231	2.306 for α=0.05
11-20	-0.64336	2.376	

However, it has been found that there are no significant correlations between the tensile strength and all geometrical parameters of the composite matrix (Tab. 2).

Tab. 2. Correlation coefficients (r) between tensile strength (R_m) and stereological parameter (χ)

Correlation coefficient R_m/χ	A_A [%]	$N_{L\|\|}$ [1/mm^2]	$N_{L\perp}$ [1/mm^2]	N_L [1/mm^2]	N_A [1/mm^2]	$F_{śr}$ [µm]
r	0.116022	-0.07332	-0.08401	-0.07879	0.038929	-0.08609
t_o	insignificant					

It means, that the reinforcing phase in the form of SiC precipitates plays an essential role in mechanical behaviour of the composite material investigated, especially a number of SiC precipitates related to the unit cross area (1 mm^2) and their size defined by the Feret diameter combined in the formulated parameter $\chi = (N_A/F_{śr})^{1/2}$.

It is also important that there are no any correlations for the samples marked as 1-10 being before machining, but in the case of samples numbered 11-20 (after machining) such correlations were ascertained. This fact should be explained by microstructural inhomogeneities existing on the sample edges before the machining.

4. New generation of brake discs -quality assessment method [6.7]

The quality of vehicle brake discs produced from the aluminum alloy matrix composite was assessed by means of the image analysis as well as by friction coefficient determination. In the first step of the quantitative metallographic investigations a distribution of geometrical parameters of reinforcing phase precipitates within the composite matrix was considered. The locations from where the specimens were taken and the orientation of the cast (top, middle and bottom) are shown in Fig. 4. The microstructure of the composite, observed for this brake discs, is shown in Fig. 5.

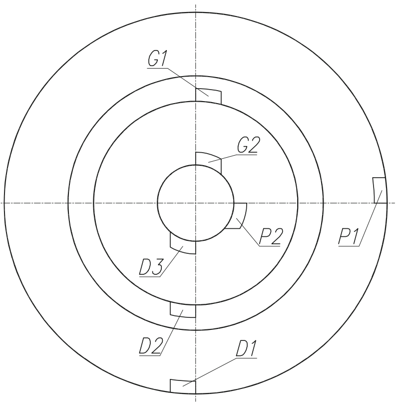
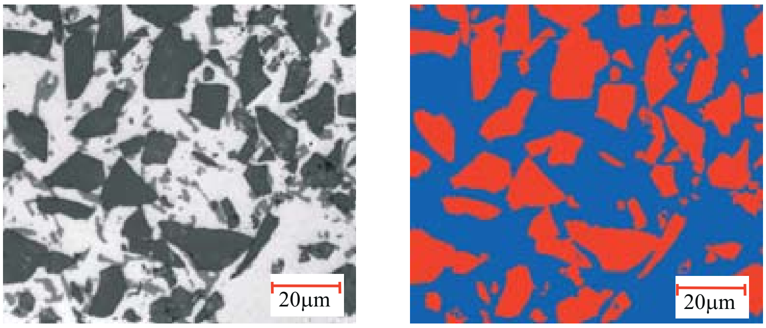


Fig. 4. Scheme illustrating the sample locations at the composite cast of brake disc



G1-a G1-b

Fig. 5. Microstructure of the brake disc: a) real image, b) binary image prepared for quantitative analysis (reinforcing phase SiC - grey and matrix - black)

The same geometrical parameters as those considered in previous sections, except the Feret diameter, were determined. In this case they are related to the reinforcing phase (SiC precipitates), only. Additionally, the average free path (λ) was determined on the basis of definition proposed by Fullman [8] in the following form:

$$\lambda = \frac{1 - V_V}{N_L} [\, mm \,] . \tag{2}$$

The results of quantitative analysis are summarized in Tab. 3.

Tab. 3. Geometrical parameters of the reinforcing phase (the standard deviations are given in parentheses)

Destgnation Geom. param.	Sampling destgnation						
	G1	G2	D1	D2	D3	P1	P2
Volume fraction V_V [%]	22.29 (7.92)	23.09 (6.85)	22.15 (6.53)	19.99 (6.09)	22.31 (7.09)	21.24 (5.90)	22.98 (5.77)
Density N_A [1/mm^2]	3896.7 (954.5)	3485.3 (789.4)	3237.9 (751.7)	3048.2 (749.3)	3672.4 (848.2)	3062.1 (735.7)	3977.8 (845.4)
Estimator of relative area (horizontal) $N_{L\parallel}$ [1/mm]	242.348 (46.033)	217.577 (30.865)	229.673 (28.067)	222.256 (30.744)	195.096 (31.013)	190.956 (22.436)	206.152 (25.625)
Estimator of relative area (perpendicular) $N_{L\perp}$ [1/mm]	243.738 (46.135)	218.557 (31.276)	229.865 (27.147)	222.696 (30.268)	195.561 (30.374)	192.279 (22.890)	204.805 (26.189)
Estimator of relative area (average) $N_{L(average)}$ [1/mm]	243.043	218.067	229.769	222.476	195.329	191.618	205.479
Average free path λ [mm]	0.003	0.004	0.003	0.004	0.004	0.004	0.003

The results show the similar distribution of all geometrical parameters determined, giving as a consequence the confirmation of microstructural homogeneity. It is especially important in such situations when there is a need to obtain the high and repeatable wear resistance of brake discs and effective and safe braking system.

The results of friction coefficient investigations for composite material exhibit better wear characteristics than those achieved for the brake discs made from the traditional materials such as the cast iron for example (see Fig. 6 and Tab. 4).

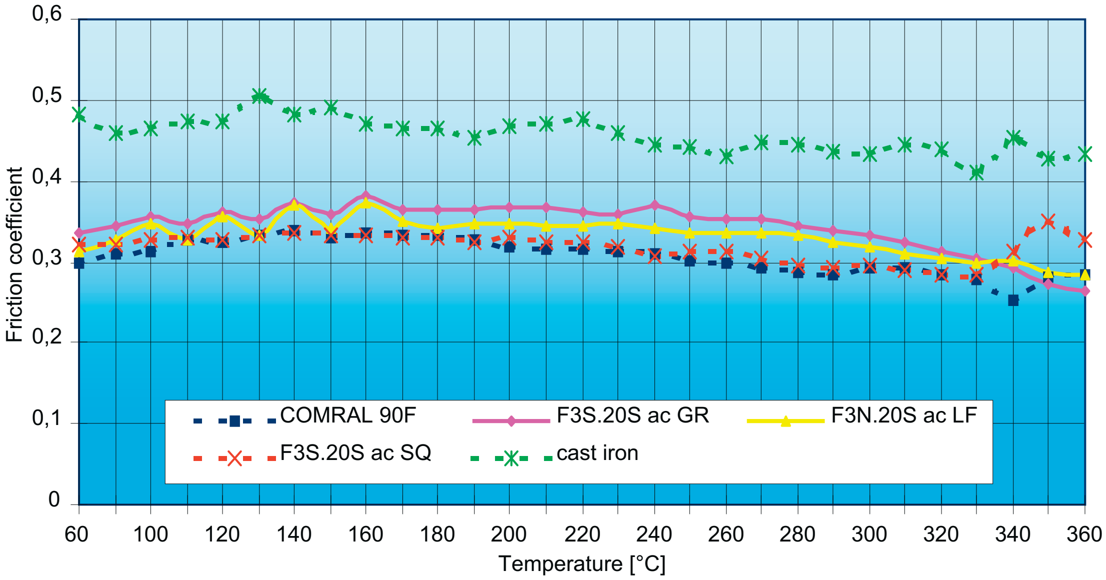


Fig. 6. Variation of the friction coefficient as a function of temperature

Tab. 4. Linear wear and loss-weight results of tested materials

Sample No.	Material	Linear wear of anti-sample DB 857 [mm]	Material linear wear [mm]	Loss-weight of anti-sample [g]	Material loss-weight [g]
1	F3S.20S$_{ac}$GR	0.50	0.081	0.9157	0.1819
2	F3S.20S$_{ac}$SQ	0.46	0.068	0.7485	0.0898
3	F3N.20S$_{ac}$LF	0.49	0.074	0.7902	0.0990
4	COMRAL 90F	non measured	1.215	1.2203	1.7141
5	Cast iron	0.23	0.058	non measured	non measured

5. New generation pistons- quality assessment method [7, 8]

A quality of the pistons produced from composite materials of aluminum alloy matrix was assessed by means of the image analysis as well as by thermal shock resistance determination. At first, a distribution of the geometrical parameters of reinforcing phase precipitates in the composite matrix was analyzed on the basis of quantitative metallographic investigations. A typical microstructure of the composite is shown in Fig. 7. The sample, low-cut from the piston, was analyzed in an non etched state, in which Al-Si eutectic (composite matrix) and precipitates of Al_2O_3 reinforcing phase are visible. Quantitative metallographic analyses were performed on cross-section (Fig. 7a) and on longitudinal-section (Fig. 7b) taken from top and bottom part of the piston for the microstructural anisotropy determination.

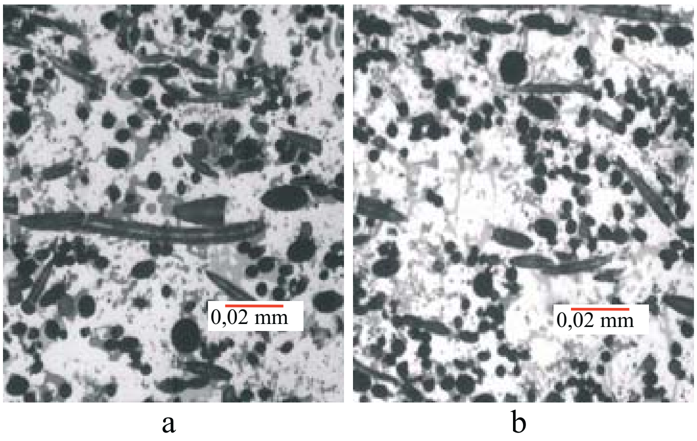


Fig. 7. Microstructure of piston with crown ceramic insert (perform MORGAN - based on short fiber Al_2O_3 with SiO_2 binder after squeeze infiltration by AlSi12CuMgNi alloy), cross-section in relation to piston traffic (a) and longitudinal-section in relation to piston traffic (b)

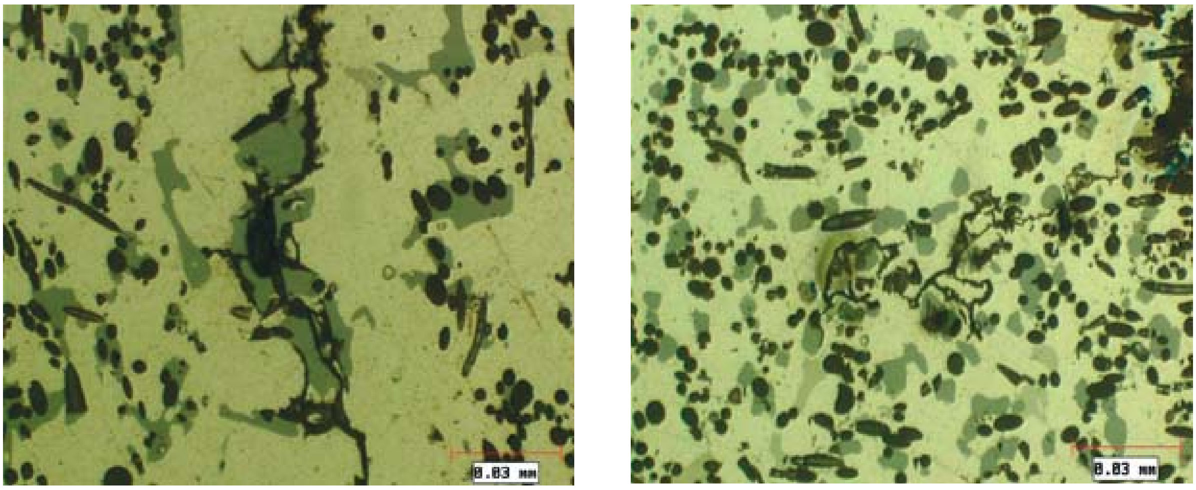
Except of the average free path (λ) and Ferret diameter (F), the same geometrical parameters as those previously considered were determined for the reinforcing phase (Al_2O_3 - short fibers) and composite matrix (Al-Si eutectic). Moreover, the anisotropy coefficient (Ω) was calculated.

The results are put together in Tab. 5. They show that there are no significant differences between the geometrical parameters determined on the cross- and longitudinal- sections in relation to the piston top and its bottom part. This fact concerns the Al_2O_3 short fibers as well as the alloy matrix (eutectic - Al/Si).

The similar geometrical parameters of composite microstructure can be also used to predict some repeatable and reproducible exploitation properties such as the thermal shock resistance for example. Only this exploitation property was analyzed in the case of tested composite materials considered in this work. An example of some microstructural defects are shown in Fig. 8. for AK12/Al_2O_3 - 20%.

Tab. 5. Geometrical parameters of Al_2O_3 short fibers and precipitates of Al-Si eutectic in the piston composite material (values of standard deviation are put in parentheses)

Geometrical parameter	Al_2O_3 fibers		Al-Si eutectic	
	⊥ direction	|| direction	⊥ direction	|| direction
A_A [%]	28.23 (3.40)	26.95 (4.39)	26.70 (2.02)	26.62 (2.23)
$N_{L\|\|}$ [1/mm]	376.68 (24.94)	386.29 (26.58)	1128.07 (59.50)	1270.83 (58.80)
$N_{L\perp}$ [1/mm]	447.26 (27.96)	459.16 (32.69)	1239.76 (69.89)	1374.60 (69.55)
N_A [1/mm^2]	30179.94 (5155.80)	25347.63 (5045.51)	162414.70 (12685.56)	160943.39 (12661.45)
Ω (anisotropy coefficient)	0.84 (0.03)	0.84 (0.04)	0.91 (0.02)	0.93 (0.02)



a b

Fig. 8. Microstructure of composite material (AK12/Al_2O_3 - 20%), 5000 cycles, crack length - max 1 mm, before heat treatment (a), after heat treatment (b)

The thermal shock resistances for various types of composite materials are presented in Fig. 9.

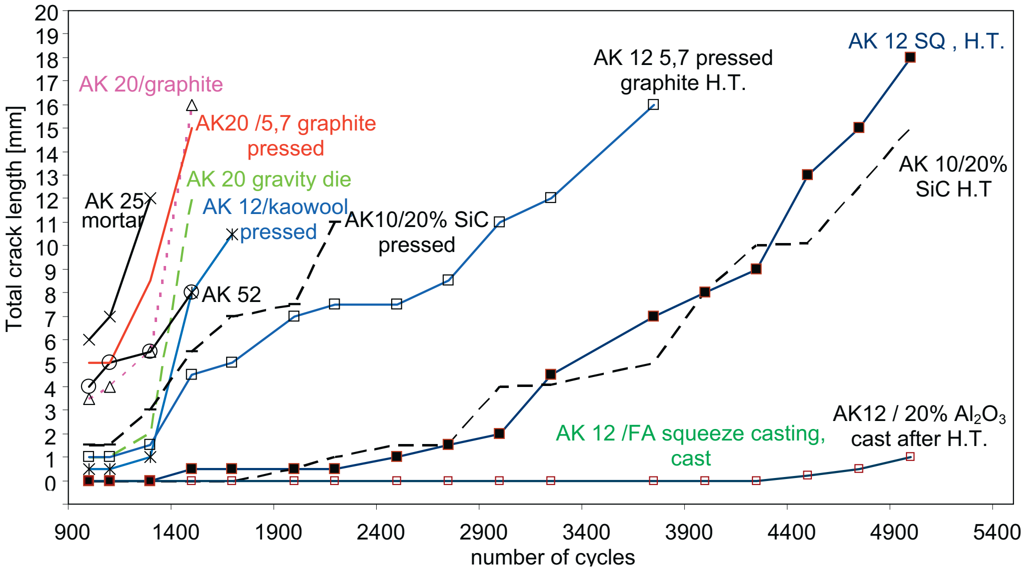


Fig. 9. Thermal shock resistances of selected composite materials

The best thermal shock resistance was obtained, in the case of AK12 composite with Al_2O_3 short fibers, in cast heat treated.

6. Summary

The paper shows the methods of quality assessment of composite materials as well as the possible applications of modern composites in the motor industry: aluminum alloys reinforced by SiC (brake discs for vehicles) or aluminum alloys with Al_2O_3 short fibers (pistons for combustion engines in vehicles).

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