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Properties of Sintered P/M Aluminium Composites

S. Müller, Th. Schubert**, F. Fiedler***, R. Stein*, B. Kieback**, L. Deters****
** Schunk Sintermetalltechnik GmbH, Roßtrappenstraße 62, 06502 Thale, Germany*
*** Fraunhofer IFAM, Winterbergstraße 28, 01277 Dresden, Germany*
**** TU Otto-von-Guericke-Universität Magdeburg, IMK,*
Universitätsplatz 2, 39106 Magdeburg, Germany

1. Abstract
The Powder Metallurgy (P/M) manufacturing route with pressing, sintering and sizing allows the near net shape fabrication of precision parts made from many different alloy systems. The automotive industry is the most lucrative market for P/M aluminium. However, the low wear resistance, compared to other materials, hampers its application in components (e.g. sprocket) where wear resistance is important. Therefore, in the past different P/M aluminium alloys, especially designed for sintering and reinforced with silicon or hard ceramic particulates (e.g. alumina, zirconium silicate, fly ash) were developed. In this study, the mechanical and tribological behaviour of composites reinforced with sharp edged or spherical ceramic particles was investigated. The wear resistance was evaluated during sliding against hard steel under lubricating conditions at elevated temperatures.

2. Introduction
Near net shape parts of sinter steel manufactured by the P/M process are indispensable in combustion engines, especially for passenger cars. The requirement to reduce weight of the cars has produced a lot of efforts to replace such steel parts by light weight solutions in the last years. Particulate reinforced aluminium matrix composites offer a considerable potential for enhanced wear resistance [1-4]. The improved wear resistance of these composites is generally attributed to the presence of the hard reinforcing particles. The challenge is the selection of the most suitable combination of aluminium alloy matrix and hard particles. Several requirements such as sufficient hardness and strength of the inclusions, good bonding to the matrix, low price and density of the particles have to be met. In addition, we have to consider both, the wear resistance of the P/M aluminium material and of the wear counterpart. But, wear is not a material property. Therefore, the development of a wear-resistant material for a certain application needs a suitable wear test system because usually it is not possible to test all material variants on original engine test stands. The intention of this investigation is to detect an adequate material for a sprocket (particularly camshaft) of the control assembly, in conjunction with a good P/M processibility (pressing, sintering, sizing).

3. Experimental
A lot of different powder blends was investigated foregoing. Regarding on a high wear resistance and an adequate strength some variants have been chosen. Fly ash as reinforcing material was disregarded because of its insufficient chemical and mechanical stability.
In other works [1, 3, 4] as well as in the preliminary investigations for this paper, the reinforcing particles typically amounted 4-20 volume %. With regard to the maintenance of the properties of matrix material and processibility the reinforcing amount was limited to 2 volume % in this work.
The compositions of the powder premixes used are shown in Table 1.

Name	Base material [wt.%]						Reinforcing material
	Al	Si	Cu	Mg	Sn	Fe	vol.%
A	Bal.	14.8	2.50	0.58			-
B	Bal.	0.67	4.30	0.47		0.09	2 $ZrSiO_4$ edged, <75 µm
C	Bal.	0.30	3.09	1.46	0.61	0.11	2 $ZrSiO_4$ edged, <75 µm
D	Bal.	0.30	3.09	1.46	0.61	0.11	2 (ZrO_2 +SiO_2) spheric, 0-63 µm
E	Bal.	0.34	3.04	1.47	0.61	0.13	2 Al_2O_3 edged, < 100µm

Table 1: Chemical composition of investigated alloys

Mixed powders were pressed to blanks of 58 mm diameter and 20 mm height as well as tensile test bars according DIN ISO 2740 and unnotched test bars for impact strength according DIN ISO 5754. Green compacts of alloy A were pressed at 600 MPa and of the alloys B – E at 300 MPa.
Previously the pressing behaviour of powders was investigated by using a modified universal test machine EDZ 20, using a cylindrical press tool, diameter 11.28 mm.
For delubricating and sintering of pressed parts a continuous belt furnace, with 100% nitrogen atmosphere (dew point < -45°C) and sinter temperatures between 560 and 625°C (45 – 60 min), depending on the composition and the geometry of the specimens, was used.
The sintered parts were solution annealed, 510°C for 45 min, water quenched and optionally naturally (T4) or artificially (T6) aged. However, only artificially aged specimens were used for the wear tests. The blanks for the wear tests additional were sized with the objective of a surface smoothing (before artificial annealing). A notable further densification was not achieved by sizing because of the relatively high sinter density.
For wear resistance tests, the blanks were turned into smaller discs (diameter 24 mm, height 9 mm) using the sized, unmachined front sites of the blanks (axial) as test surface. Wear resistance of sprockets for roller chains was simulated by linearly reciprocating tribometer. The test arrangement is described in Fig. 1.

- Load F_N: 472 N
- Frequency: 50 Hz
- Stroke: 1,5 mm
- Temperature: 90 °C
- Lubricant: Motor oil 5W30
- Test duration: 24 h
- Total friction run: 12960 m
- Average speed: 0,15 m/s
- Stop criterion: effective friction coefficient > 0,2

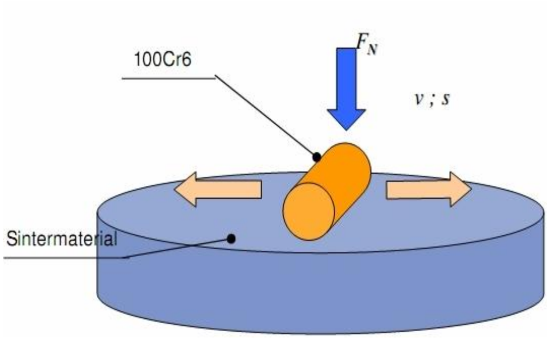


Fig. 1: Scheme of the linearly reciprocating tribometer

4. Results and discussion

Press / Sintering behaviour

Considering that alloy A has to be pressed at 600 MPa, while alloys B – E only need the half of this compacting pressure, a lower tool wear is expected during the compaction of the particle reinforced powder mixtures compared to the silicon containing alloy A (Fig. 2).

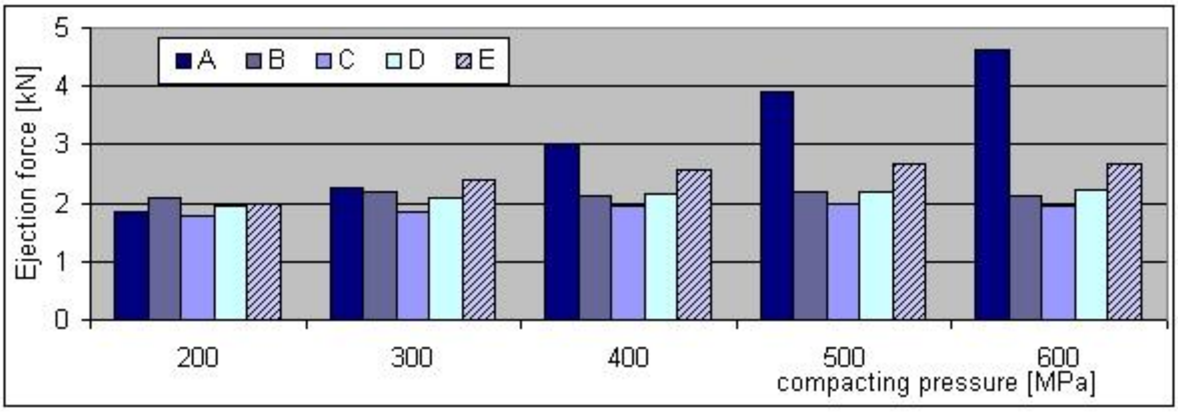
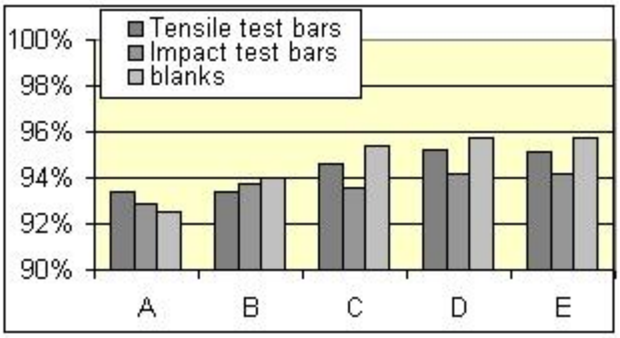


Fig. 2: Ejection force of alloy A – E depending on compaction pressure

The highest green densities were achieved in the case of particle reinforced powder blends C-E based on the same aluminium matrix (Fig. 3). The reduced compressibility of the powder blend A is also confirmed by the obtained low green densities of these compacts.
During the sintering of the green compacts different shrinkages (Fig. 5) were observed for the investigated powder blends as a result of the change of density from the green to sinter part (Fig. 4).

The differences of the sintering behaviour are mostly based on the used aluminium matrix compositions and their intrinsic sintering mechanism.



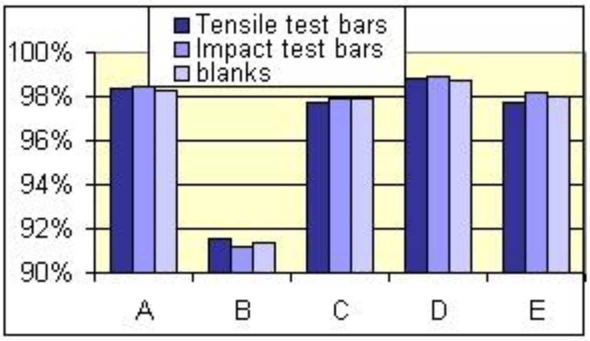


Fig. 3: Green density of alloy A – E as a the percentage of respective full density.

Fig. 4: Sinter density of alloy A – E as a percentage of the respective full density.

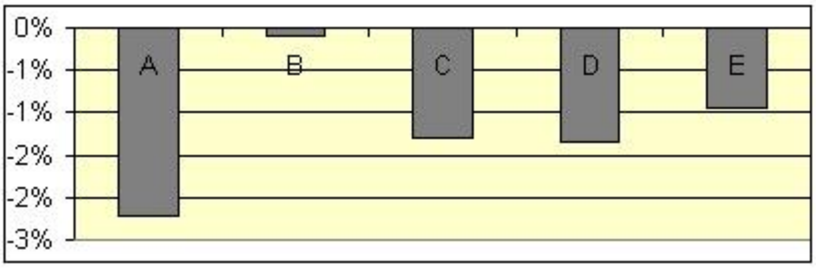


Fig. 5: Dimensional change from the green to the sintered tensile test bars [%] of alloy A – E.

Typical microstructures of the sintered materials are shown in Fig. 6.

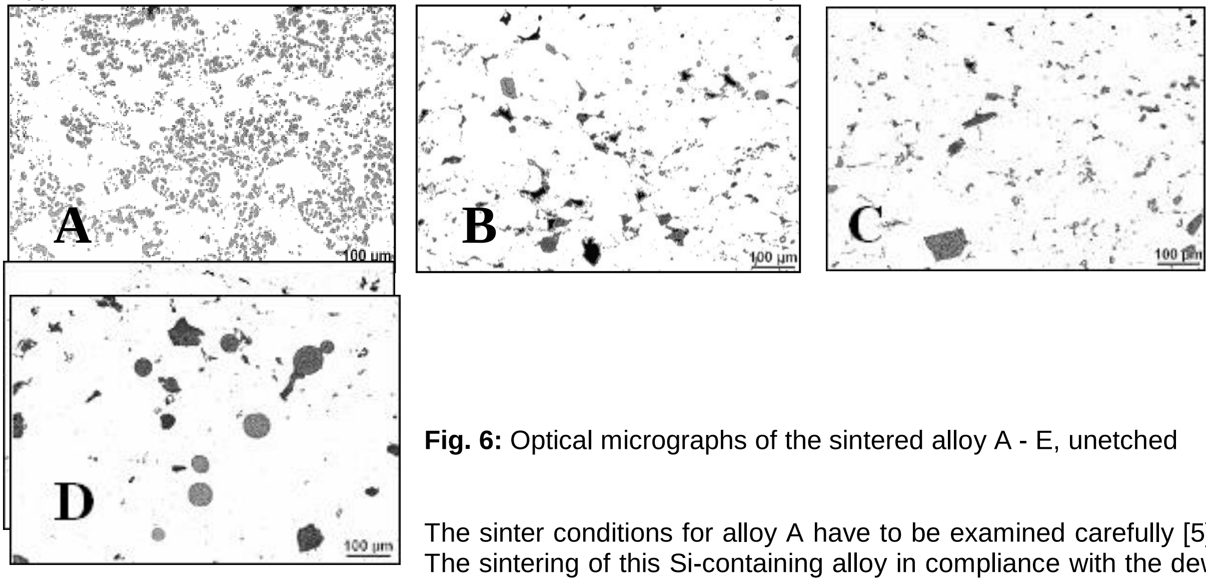


Fig. 6: Optical micrographs of the sintered alloy A - E, unetched

The sinter conditions for alloy A have to be examined carefully [5]. The sintering of this Si-containing alloy in compliance with the dew point of < -40°C in the furnace atmosphere, commonly demanded for sintering of aluminium, is not sufficiently yet. Because of the absence of hydrogen in a pure nitrogen atmosphere, there is no equilibrium between O_2 und H_2O. For this reason the additional control of the oxygen content of the atmosphere is important. The residual oxygen impurities can lead to the formation of MgO on the alloyed powder particles at the surfaces of the compacts. Depending on the thickness of these oxide layers the further sintering was blocked and resulted in the formation of porous surface areas [6]. As a result of this self getter effect of the green parts the oxygen content of the furnace atmosphere was significantly reduced. For this reason the loading, the number of parts during sintering, was optimised and kept constantly.

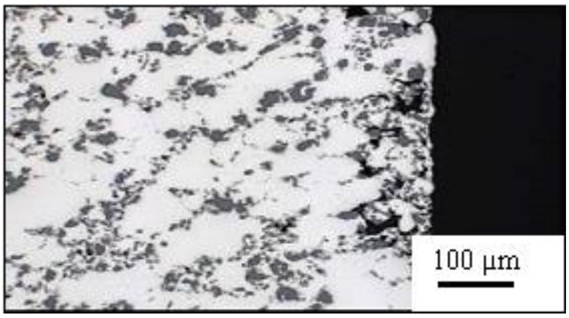


Fig. 7: Optical micrograph of alloy A with surface porosity, unetched.

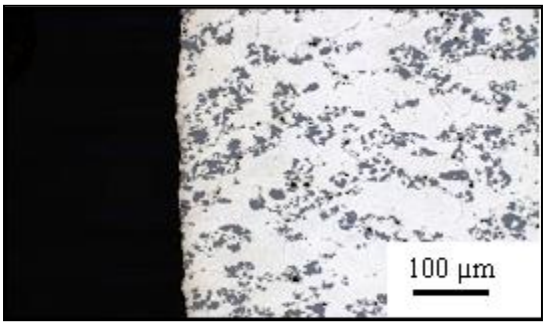


Fig. 8: Optical micrograph of alloy A without surface porosity, unetched.

Mechanical properties

The achieved mechanical properties of the sintered materials are shown in Figs.9 – 11.

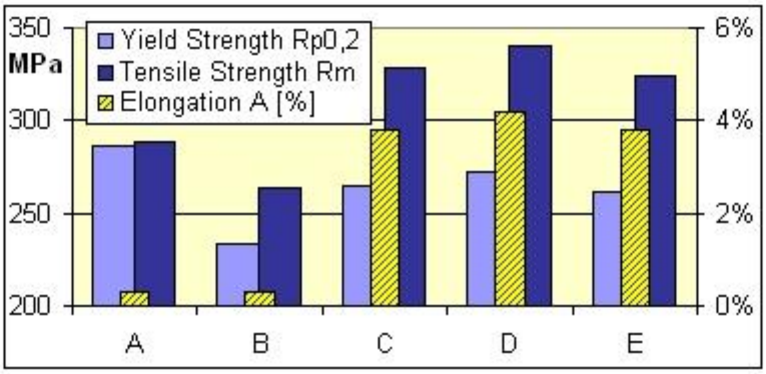


Fig. 9: Tensile strength and elongation in T6 condition

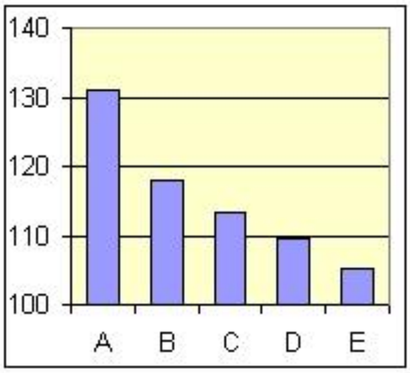


Fig.10: Brinell-Hardness in T6 condition (blanks)

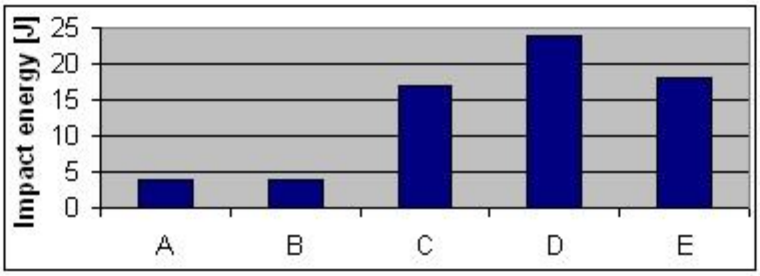


Fig.11: Impact energy in T6 condition (unnotched test bars)

In T6-condition, the highest elongations were achieved in case of the particle reinforced powder blends C-E, just as very good impact energies.

Alloy A is characterised by the best hardness value.

Tribological behaviour

The test blanks of alloy A – E and additional the unreinforced base alloys for B and C/D were tested on a linearly reciprocating tribometer as described. Three samples per variant were the minimum quantity. Fig. 12 shows the average abrasion of P/M aluminium blanks and the roll. Alloy A shows excellent wearing behaviour. The abrasion of the P/M aluminium discs and steel rolls were increased for samples B, C and E compared to alloy A.

The friction coefficient for all tested variants was in the range between 0.11 and 0.14.

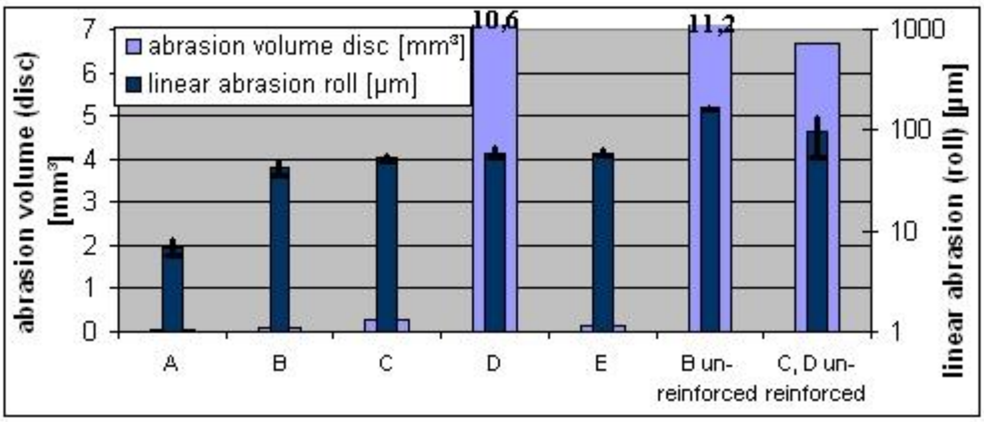


Fig. 12: Linearly reciprocating tribometer tests: abrasion of blank and test roll

All tests of alloy D had to be cancelled because of achieving the stop criterion. That is probably caused by the low interfacing bonding and fracture strength of the used spherical ceramic particles. The tests of unreinforced variants of alloys B and C/D had to be cut short too.

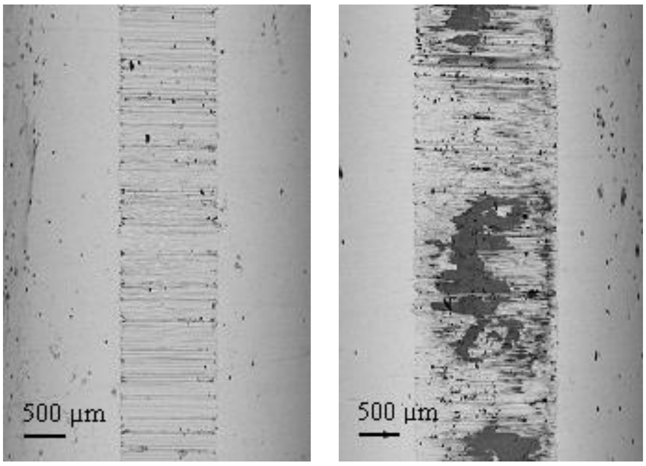


Fig. 13:
SEM micrographs of roll after linearly reciprocating tribometer test, alloy C, left an unproblematic test run, right a cancelled test run respectively

Some tests of alloy C must be also stopped because of a critical increase of friction.
These test runs show adhesive wear, i.e. aluminium was transferred from the disk to the roll. Not cancelled test runs show only abrasive wear (Fig. 13).

To understand the breakdown of some test runs different influencing factors were considered, exemplary for alloy C.

It was assumed that surface effects could be a reason for the different wear behaviour. Therefore, a sintered and sized specimen was turned and tested again. Both, the abrasive disk volume and the roll abrasion were clearly decreased and achieve results in a range comparable to alloy A (Fig.14). A similar improving effect was observed after sieving the reinforcing material, using 100 µm mesh size. Possible agglomerates of the hard particles were removed by sieving.

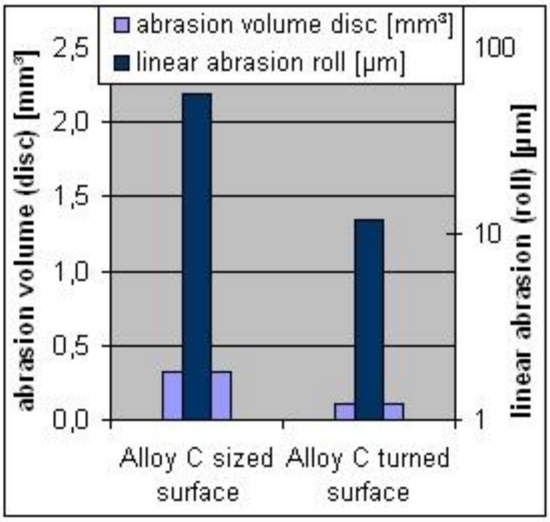


Fig. 14: Linearly reciprocating tribometer tests: abrasion of blank ant test roll, alloy C, sized and turned surface

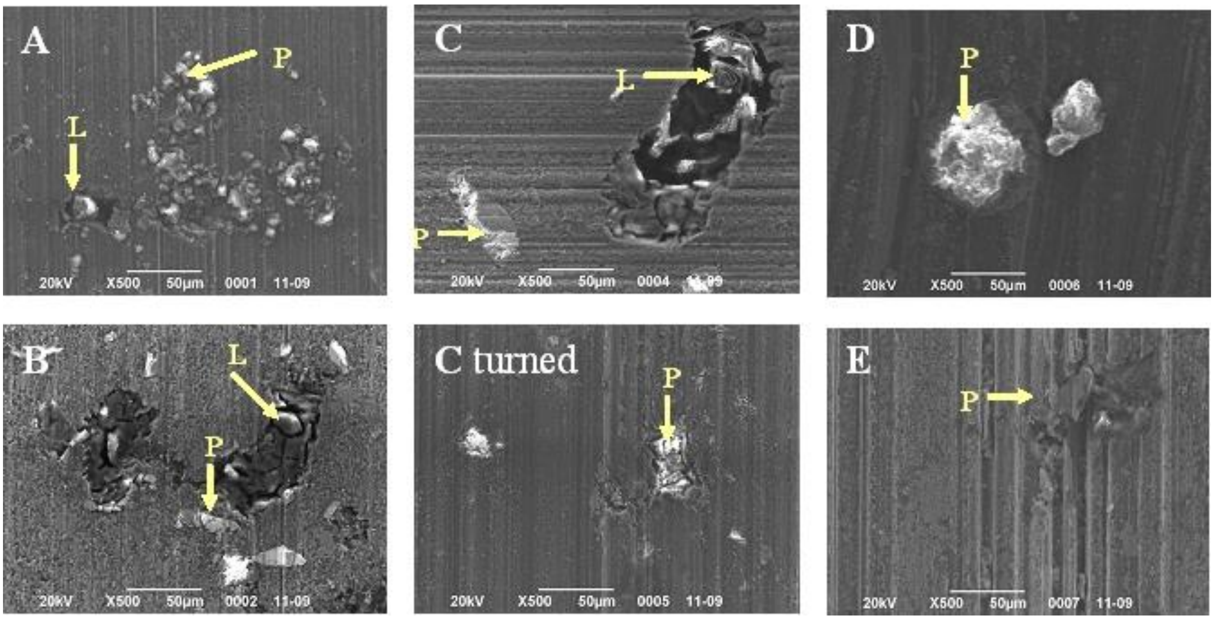


Fig. 15: SEM micrographs of discs after linearly reciprocating tribometer test, alloys A – E

The surfaces of selected tested P/M aluminium discs were also investigated by SEM (Fig. 15). Hard particles "P" of the alloys A, B and C are partially broken out. Obviously, the fragments are embedded in the softer aluminium matrix material again. In addition, lubricants "L" can be fixed into the residual spaces as local oil reservoir. That can be beneficial for wear behaviour, if the space sizes are limited. In case of the alloys B and C the used reinforcement material was $ZrSiO_4$. Obviously, the first blends contained agglomerates of the hard particles with a size > 100 µm, which were broken out under load. By sieving these agglomerates were removed. The same effect is visible after turning the disc. No large particles remained in the surface area, resulting in an evident improvement of the wear resistance. The spherical ceramic particles of Alloy D were insufficiently stable and fixed in the matrix. The particles were pulled out and caused the collapse of the wear system. Alloy E is characterised by braking out and embedding again of the hard, small ceramic particles.

5. Conclusions

The reinforcement of P/M aluminium alloys with small amounts of hard particles (2 volume %) leads to an significant increase of the wear resistance compared to the base alloy without a noticeable degradation of the mechanical properties. It also can be an alternative to the 14% Si containing Al-PM-Alloy which is the best material in the simulated test for roller chains (by linearly reciprocating tribometer) but more difficult to press and to sinter. That requires a suitable morphology and size of the ceramics to avoid the breaking out of large particles. In this investigation edged particles with sizes less than 75 µm were promising. Meanwhile, the breaking out and embedding again of small hard particles into the aluminium matrix is beneficial for the wear behaviour due to the formation of spaces as lubricant reservoir.

The test surface has an important influence on the abrasion of wear partners, caused of a possible non-uniform particle distribution.

For finally evaluation of the suitability of the materials in the sprocket / roller chain system tests on engine test bench are recommended. Wear resistant PM aluminium alloys have a large potential for lightweight applications.

6. Acknowledgement

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7. References

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