Sintering and Properties of New P/M Aluminium Alloys and Composites

A.Dudhmande*, Th. Schubert**, M. Balasubramanian*, B. Kieback**/***

Composites Technology Centre, Department of Metallurgical and Materials Engineering, IIT Madras, Chennai - 600036, India.
*** Fraunhofer IFAM, Winterbergstraße 28, Dresden - 01277, Germany*
**** TU Dresden, Institute of Material Science, Dresden – 01062, Germany*

Abstract

The conventional 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 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, silicon carbide) were developed. In this study, the mechanical and tribological behaviour of composites reinforced with sharp edged ceramic particles and spherical fly ash particles was investigated. The wear resistance was evaluated during sliding against hard steel ball under lubricating conditions at elevated temperatures.

1 Introduction

Particulate reinforced aluminium offers considerable potential for enhanced wear resistance. But, the drawback of Al composites reinforced with hard ceramic particles such as SiC or Al_2O_3 is the tendency of the reinforcement to cause intolerable tool wear during pressing and to act as an abrasive against the counter material in service. Therefore, an area of intensive interest is the development of wear-resistant aluminium alloy products by Powder Metallurgy processing [1-4]. P/M processing offers some significant advantages over casting, particularly in its ability to produce hypereutectic AlSi alloys with relatively fine Si particles, which can provide a wear-resistant and machinable product [5]. Another possibility for the improvement of wear resistance is by the use of alternative reinforcements such as $ZrSiO_4$, having a non-sharp morphology [6]. Fly-ash, which is an industrial waste, can also be used as reinforcement for the aluminium matrix [7-9]. Fly ash is a predominantly inorganic residue obtained due to coal combustion in furnaces and contains fine mainly silica and alumina with minor amounts of calcium and magnesium oxides. The characteristic spherical nature of the fly ash particles can prove to be beneficial as far as the counterpart wear is concerned [8]. The present research aims at the development of Aluminium - fly ash composite based on commercially available ready-to-press powder mixtures as the matrix materials and compares their strength and wear behaviour with other Aluminium matrix composites.

2 Experimentation

As a starting material, Aluminium alloy powder premixes Alumix 431-Nr.10490/D (later labelled 431*), Alumix 431* + 13 vol% SiC (F240), and Alumix 231 were obtained from ECKA Granulate GmbH, Germany, whereas AMB2712, an unreinforced Al-Cu-Mg alloy and AMB2915, which is a ceramic reinforced aluminium alloy powder premix, were supplied from AMPAL Inc., USA, as reference materials. The compositions of the powder premixes used are shown in Table 1.

Table 1: Chemical compositions of the investigated alloys.

Name	Chemical composition in wt%						Reinforcement
	Al	Cu	Mg	Si	Zn	Sn	
Alumix 231	Bal	2.4-2.8	0.5-0.8	14-16	-	-	-
Alumix 431*	Bal	1.5-2,.0	2.0-3.0	-	5.5-6.5	0.1-0.3	unreinforced, 13 vol% SiC, 15 vol% HKV
AMB 2712	Bal	3.6-4.0	0.8-1.2	0.6-0.9	-	-	-
AMB 2915	Bal	2.8-3.2	1.3-1.7	0.15-0.35		0.45-0.75	15 vol% ceramic

(* equivalent to Alumix 431 Nr. 10490/D)

Fly ash of the type HKV was obtained from SAFA GmbH, Germany. The fly ash was first sieved to get a particle size of 45-100µm. Additional mixtures of Alumix 431* + 15 vol% fly ash were made by mixing the powders in a turbula mixer for 10 min. The mixtures were pressed into tensile specimens at 250 – 500 MPa according to EN ISO 2740. For wear testing, discs of 55 mm diameter and 15 mm height were pressed at 300 MPa. The pressed samples were first de-lubricated and subsequently sintered at 560-630^{o}C for 20-60 min, depending on the type of the material, in nitrogen atmosphere (dew point < -50°C). Age-hardening of the sintered specimens was also performed in dependence of the material composition (solution annealing, 470-500^{o}C for 60 min, water cooling, and ageing, 130-170^{o}C for 17-24 h).

Tensile testing of the samples was carried out on the tensile testing machine 1476 of Zwick, Germany (EN 10 002-1). Brinell hardness testing was performed at a load of 61.25 N using a steel ball of 2.5 mm diameter. E-moduli were measured by ultrasonic method. Wear testing of the discs was carried out in a tribometer TRM 1000 of Wazau, Germany against a 10 mm diameter steel ball at a temperature of 120^{o}C with normal loads varying from 20-60N and fully immersed in oil. The speed of rotation of the disc varied cyclically from 0 – 400 rpm. The friction coefficient was calculated from the measured tangential force. During the tests, the temperature of the system and the total linear wear were recorded. The ball wear was reported from the initial and final measurements of the ball diameter, whereas the disc wear was reported from the surface profile measurements done before and after the testing.

3 Results and Discussion

Fig. 1 shows a comparison between the densification behaviour of composite mixtures made from Alumix 431*, 431* + SiC and 431* + HKV_{45-100}. As seen from the Fig. 1, Alumix 431* and its composites exhibit an excellent sintering response. Relative densities of 96 – 99% T.D. were obtained for the Alumix 431* + SiC and Alumix 431* + fly ash composites. This is due to the enhanced sintering response of Alumix 431*, which is a recently developed aluminium powder premix by ECKA Granulate GmbH, showing improved sintering activity because of a predominant supersolidus sintering [10].

In spite of the high densification, the fly ash reinforced composite shows inferior mechanical properties compared to the SiC reinforced composite as can be seen in Fig. 2. But, the mechanical properties of Alumix 431* + HKV are still comparable to that of AMB 2915. It is assumed, that a reduced interfacial bonding of the fly ash particles can cause this lower strength behaviour. But, the comparison of the Figs. 3 and 4 suggests a separation between well and poorly bonded particles; the latter should lead to a degradation of the properties. These critical particle fractions have to be identified by future work for improving the mechanical behaviour of these composites.

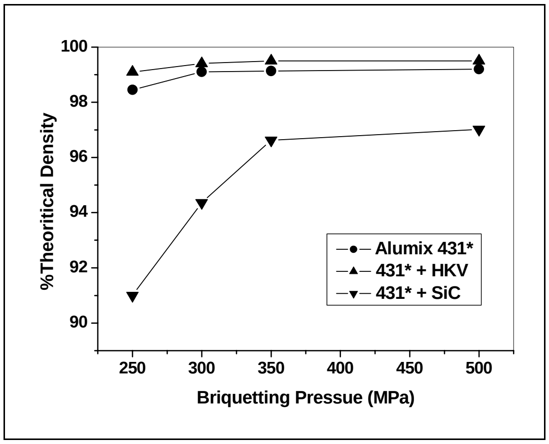

Fig. 1: Densification behaviour of Alumix 431*, Alumix 431* + SiC and Alumix 431* + fly ash.

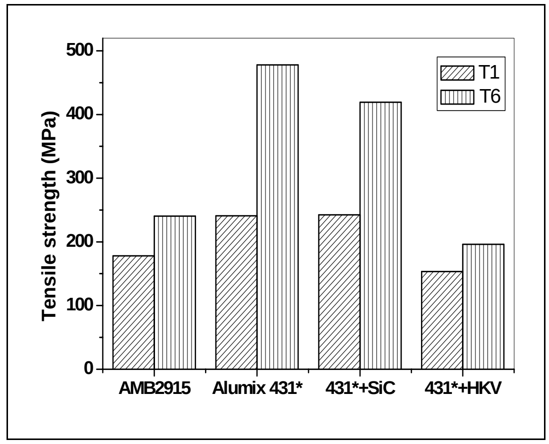

Fig. 2: Tensile strength of sintered aluminium alloys and composites in the T1 and T6 state.

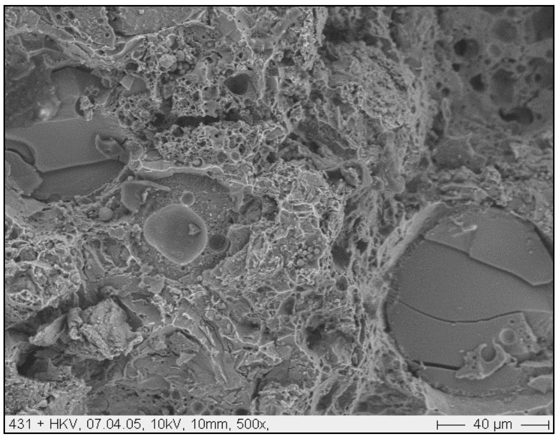

Fig. 3: SEM fractograph of the broken tensile sample of Alumix 431* + HKV showing well bonded fly ash particles.

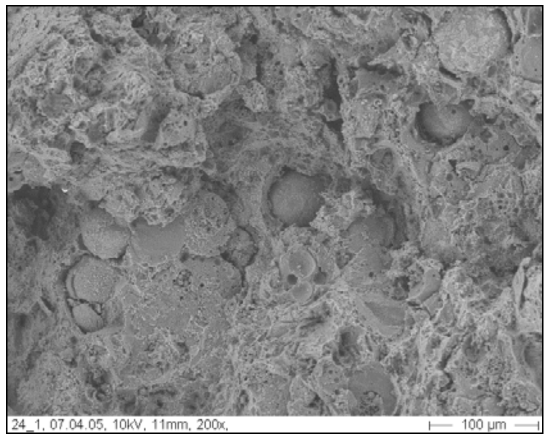

Fig. 4: SEM fractograph of the broken tensile sample of Alumix 431* + HKV showing poorly bonded fly ash particles.

In addition to this, the fracture of some of the fly ash particles during pressing at high loads (Fig. 5) can also contribute to the low strength of the composites. Fig. 6 suggests, that some reinforcement clustering can degrade the strength behaviour of Alumix 431* + SiC as compared to the unreinforced Alumix 431*.

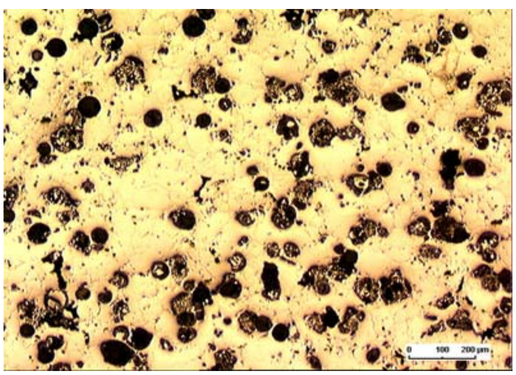

Fig. 5: Optical micrograph of Alumix 431* + fly ash (HKV).

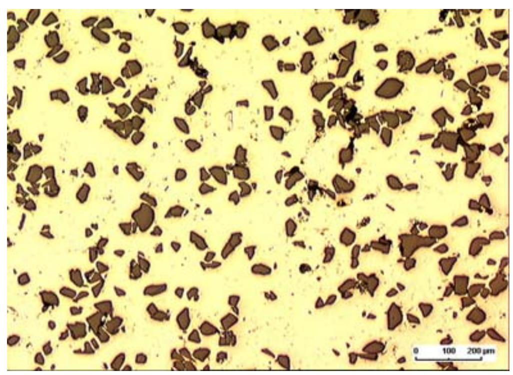

Fig. 6: Optical micrograph of Alumix 431* + SiC.

Thus, suitable mixing methods combined with a careful selection of the particle size must be developed in order to improve the reinforcement distribution in the matrix material. Table 2 summarises the mechanical properties obtained for the sintered alloys and composites in the T6 state.

Table 2: Mechanical properties (T6) of the investigated alloys.

Material	σ_{ys} (MPa)	El.(%)	Hardness HB	E-modulus (GPa)
Alumix 231	350	0.5	145	79
Alumix 431*	480	0.9	159	68
AMB2712	355	0.9	93	68
Alumix 431* + SiC	420	0.3	95	79.
Alumix 431* + fly ash	205	0.5	78	70
AMB2915	250	0.8	110	80

(* equivalent to Alumix 431 Nr. 10490/D)

Wear testing

The tribological behaviour of the sintered aluminium materials was investigated by ball-on-disk tests against typical hard steel (100Cr6). Schematic diagrams of the wear testing apparatus, employed and the loading cycle used, are shown in Figs. 7 and 8.

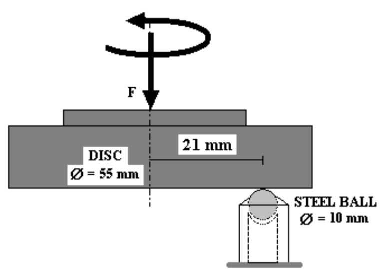

Fig. 7: Schematic view of the wear testing setup.

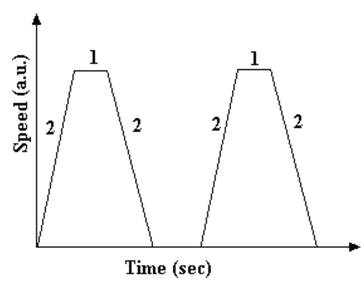

Fig. 8: Graphical representation of the load cycle used.

The loading cycle was designed to simulate the conditions of Hertzian stress as encountered in camshaft drive chain/sprocket assembly wherein the sprocket is made up of the sintered material and the chain is made of steel.

Figs. 9 and 10 show a comparison of the wear behaviour obtained for unreinforced Alumix 431* and Alumix 231. As seen in the Fig. 9, Alumix 431* shows a high wear under the testing conditions involved. A total wear of 170 µm was observed in this case, whereas the coefficient of friction remained between 0.1 to 0.8, depending on the rotation speed. This indicates a changing lubrication phenomenon during one cycle, wherein the lubricant film is formed in the beginning, but is destroyed due to the increase in rotation speed and is subsequently unable to be fully formed due to fast changes in speed of rotation. A friction coefficient > 0.2 suggests increased wear by solid-state friction. Similar results were obtained for wear testing of AMB2712. On the other hand, Alumix 231 exhibits very low wear behaviour even at 20N and 60N load (as can be seen in Fig. 10). Also, the coefficient of friction varies at a lower level between 0.05-0.2. Therefore, it does not confirm the general opinion, that increasing the hardness of a material decreases the wear rate. Table 3 summarises the wear testing results obtained for unreinforced materials. Hence, it can be concluded, that the incorporation of high amounts of silicon (14-15%) substantially increases the wear resistance of aluminium, because these medium hard particles compared to ceramics control the direct contact between the counterparts.

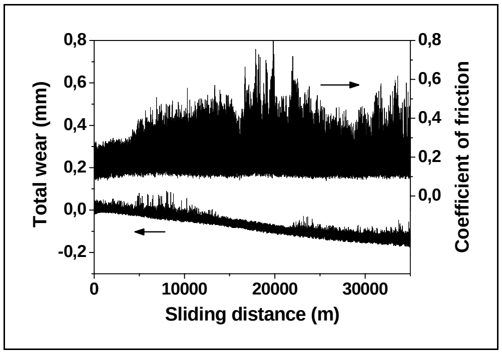

Fig. 9: Total wear curve obtained for Alumix 431*.

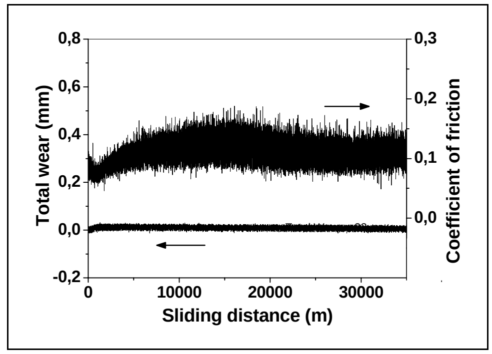

Fig. 10: Total wear curve obtained for Alumix 231

Table 3: Results of the tribological testing of unreinforced materials.

Material	Load (N)	Coefficient of friction	Total linear wear (µm)	
			Disc	Ball
Alumix 431*	20	0.1-0.8	170	0
AMB2712	20	0.1-2.0	130	0
Alumix 231	20	0.05-0.2	<5	0
Alumix 231	60	0.03-0.15	<5	0

(* equivalent to Alumix 431 Nr. 10490/D)

Figs. 11 and 12 give the comparison between the wear behaviour of Alumix 431* reinforced with SiC and fly ash particles. Table 4 shows and compares the revealed wear parameters of all reinforced composites.

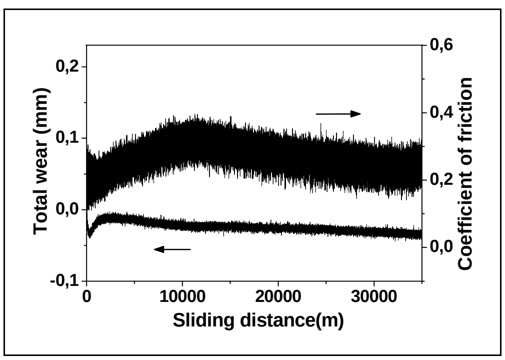

Fig. 11: Total wear curve obtained for Alumix 431* + SiC.

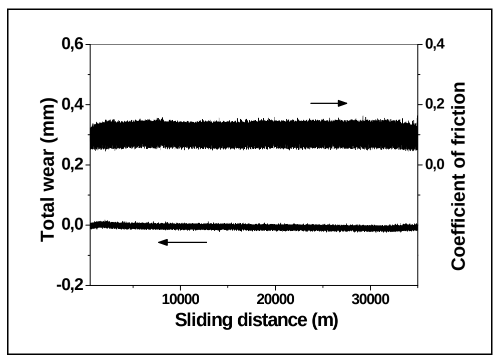

Fig. 12: Total wear curve obtained for Alumix 431* + fly ash.

Thus, it is evident, that the incorporation of hard ceramic reinforcements into the aluminium matrix causes an increase of the wear resistance of the composite material. But, an important concern is the consideration of the wear of the counterpart in the assembly. The incorporation of silicon carbide increases the wear resistance of the disc significantly, but, at the same time a high steel ball wear is revealed as is evident from the linear wear of the steel ball given in Table 4. In this case, the small contact area between the ball and the disc causes a significant Hertzian pressure at the beginning of the testing and hence, a high steel ball wear during the first hundred sliding metres. Then, the gradually decreasing pressure due to the increasing contact area between the ball and the disc lowers the wear rate of the steel ball (Fig. 11). On the other hand, Alumix 431* + fly ash (HKV) surprisingly shows a wear behaviour that compares well with Alumix 231: low disk wear as well as low counter part attack. Also, the coefficient of friction varies at a lower level between 0.05-0.25.

Table 4: Results of the tribological testing of reinforced materials.

Material	Load (N)	Coefficient of friction	Total linear wear (µm)	
			Disc	Ball
Alumix 431* + SiC	20	0.1-0.35	<5	80
Alumix 431* + SiC	60	0.08-0.2	<5	125
AMB2915	20	0.12-0.6	<5	60
AMB2915	60	0.05-0.2	<5	75
Alumix 431* + HKV	20	0.09-0.25	5	0
Alumix 431* + HKV	60	0.05-0.15	<5	0

(* equivalent to Alumix 431 Nr. 10490/D)

Conclusions

The un-reinforced P/M aluminium alloys show an extremely poor wear resistance and hence, modifications need to be done to these alloys in order to increase their wear resistance. Incorporation of ceramic reinforcements leads to an increase in the wear resistance of the composite material, but, this also causes a significant wear of the parts in contact. A substitute to this is the incorporation of spherical fly ash particles as a reinforcement material. Incorporation of fly ash significantly increases the wear resistance of the material as well as causes negligible counterpart wear. But, the tensile strength of these composites is significantly less than that of the un-reinforced material. The main reason for this is the poor interfacial bond of some of the fly ash particles with the aluminium matrix. Hence, a thorough characterization of the fly ash particles and also an identification of the useful particles is necessary to achieve an improved strength behaviour of this composite. Alumix 231 containing high silicon (14-15%) was found to be the best material for such a tribological application. This showed an excellent combination of good mechanical properties combined with high wear resistance and a low counterpart attack.

Acknowledgement

The authors would like to express their thanks to the German Academic Exchange Service for financial support.

References

[1] H. C. Neubing, *Pulvermetallurgie in Wissenschaft und Praxis*, compiled by H. Kolaska, ISL-Verlag, Hagen (2004) vol. 20, 3
[2] C. W. Hennessey, W. F. Caley, G. J. Kipouros, D. P. Bishop , *Int. J. of Powd. Met*. 41(2005)1, 50
[3] H.C. Neubing, J. Gradl, H. Danninger: *Advances in Powder Metallurgy and Particulate Materials*, compiled by V. Arnhold et.al., MPIF, Princeton, NJ, (2002) part 13, 128
[4] G.B. Schaffer, S.H. Huo: presented at Advances in Powder Metallurgy and Particulate Materials 2003, Las Vegas, NV, 2003.
[5] T. Schubert, T. Weiβgärber, B. Kieback, H. Balzer, H. C. Neubing, U. Baum, R. Braun., *Proc. of Euro PM2004*, EPMA, Shrewsbury, UK (2004), vol. 5, 627
[6] G. Jangg et al., *Mat.-wiss. U. Werkstofftech.* 27(1996), 179
[7] P.K. Rohatgi, R.Q Guo, H. Iksan, E.J. Borchelt, R. Asthana, *Mat Sci & Eng.* A. 244 (1998), 22
[8] T. Matsunaga, J. K. Kim, S. Hardcastle and P. K. Rohatgi, *Mat. Sci & Eng.* A.325 (2002), 333
[9] R.Q. Guo, P. K. Rohatgi, D. Nath, *J. Mat. Sci.* 31 (1996)20, 5513
[10] J. Gradl, H. C. Neubing, A. Müller, *Proc. of Euro PM2004*, compiled by H. Danninger, EPMA, Shrewsbury, UK (2004), vol. 4, 13