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Sintering Characteristics of Al–Pb/Fly-Ash Metal Matrix Composites

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Abstract Aluminum–lead/10 wt% fly-ash powder mixtures containing 0–20 wt% lead (Pb) were prepared. These powder mixes were compacted in the pressure range of 200–400 MPa by single action die compaction process. The prepared compacts were sintered in the temperature range of 500, 530, 560 and 590 °C in an argon gas atmosphere for duration of 45 min. For the sintered compacts, the sintered density, hardness and compressive strength were reported. Sintered density, hardness and compressive strength increased with the increase in compaction pressure. Sintered density increased whereas the hardness and the compressive strength decreased with the addition of Pb.

Keywords Metal matrix composites · Powder metallurgy · Compacts · Sintering

1 Introduction

Conventional monolithic materials generally have limitations in terms of their strength, stiffness, coefficient of expansion and density. These materials do not always provide necessary properties under all service conditions. This concern led to the development of variety of metal matrix composites (MMCs). MMCs are engineering materials formed by combination of two or more different materials of which at least one is a metallic material. These have high strength/density and stiffness/density ratios compared to the monolithic materials. Among the MMCs, the aluminum (Al) based MMCs have attracted attention in automobile sector owing to the ease of manufacturing, high specific strength and better wear resistance. The commonly used reinforcing materials in Al matrix are SiC, Al_2O_3, TiC, SiO_2, ZrO_2, fly-ash, TiO_2 etc. Among these materials, fly-ash is the most inexpensive and low density reinforcement available in large quantities. Fly-ash is a solid waste by-product obtained by combustion of coal in thermal power plants. The addition of fly-ash to Al reduces its cost and density [1]. It also increases wear, seizure, abrasion resistance and stiffness [2, 3]. These properties are desirable for materials in automotive applications. Guo et al. [4] reported an increase in hardness for Al/fly-ash composites with the fly-ash upto 10 wt%. Ramana et al. [5] observed a minimum spring back at 10 wt% fly-ash. Hence in the present work, 10 wt% fly-ash is added to Al as the reinforcing material.

During the past few decades, a number of Al-based bearing materials were developed to overcome the deficiencies like low strength and low operating temperatures of white metal bearings. Among these materials, Al–Sn alloys were used in engine applications for some time. However, Pb was tried as a replacement for tin (Sn) by various researchers because of its lower modulus of elasticity, hardness and cost. Also, Pb is more effective than Sn as a soft phase alloying addition which confers the necessary anti-scoring and anti-frictional properties. The addition of fly-ash to Pb decreases its density [6].

Production of Al–Pb/fly-ash composites by casting techniques is restricted because of the wide immiscibility

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Table 1 Specifications of the powders

S.no	Powder	Specification
1	Al	Purity 99.0 %, atomic weight 26.98, mesh size 200
2	Pb	Purity 99.5 %, atomic weight 207.20, mesh size 325

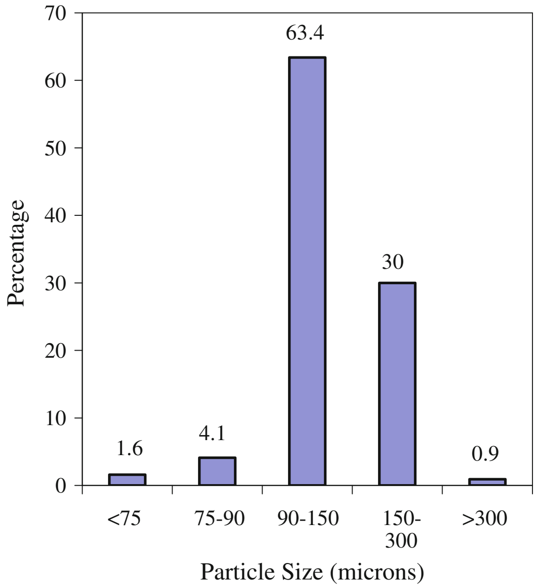

Fig. 1 Sieve analysis of fly-ash

Table 2 Chemical composition of fly-ash (wt%)

SiO_2	61.75
Fe_2O_3	1.06
Al_2O_3	27.79
TiO_2	0.95
MnO	0.14
CaO	4.36
MgO	0.73
Na_2O	0.15
K_2O	0.64
P_2O_5	0.83
SO_4	0.98
LOI	0.52

gap between Al–Pb and poor wet-ability between fly-ash particles and Al–Pb matrix. Also, there exists a huge difference in densities between Al, Pb and fly-ash particles. Because of these reasons, the powder metallurgy technique is adopted as the manufacturing method for the production of Al–Pb/fly-ash composites. The powder metallurgy technique has the advantage of attainment of close dimensional tolerances, fine structure, controllable porosity and uniform distribution of particles in the matrix material. Nath et al. [7, 8] produced Al-4.5 %Cu–Pb and Al-

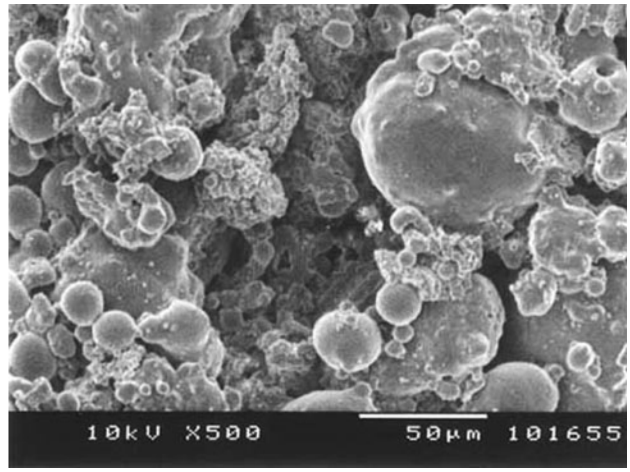

Fig. 2 Scanning electron micrograph of fly-ash particles

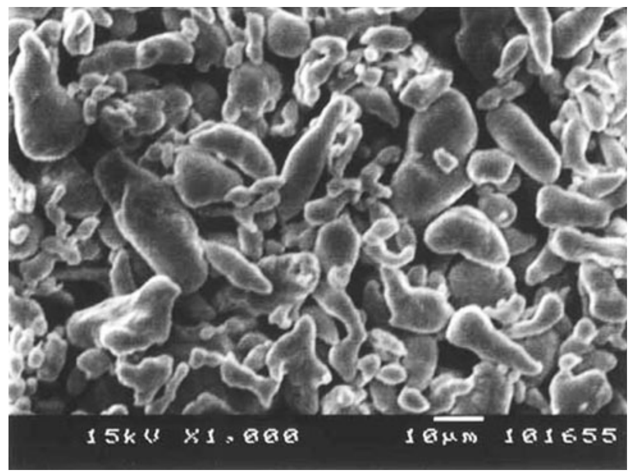

Fig. 3 Scanning electron micrograph of Al particles

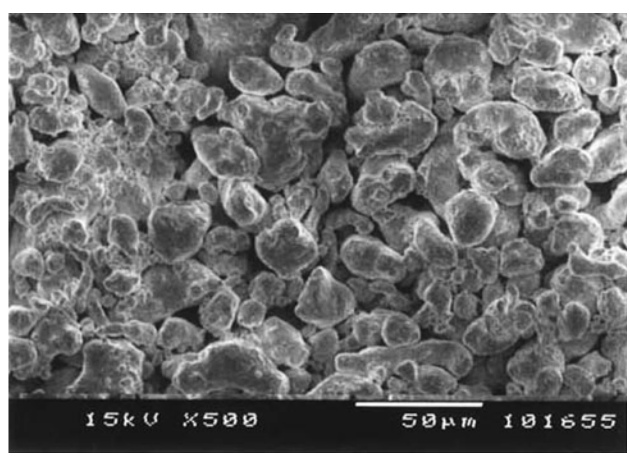

Fig. 4 Scanning electron micrograph of Pb particles

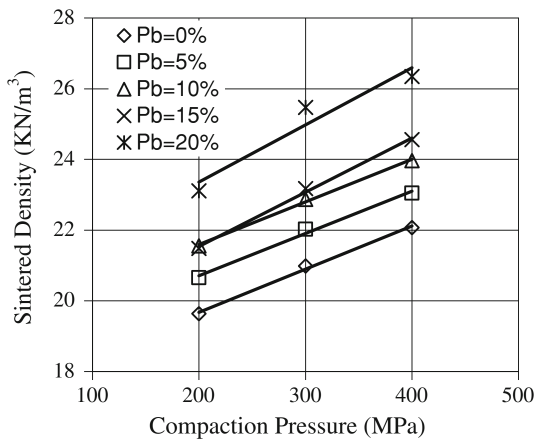

Fig. 5 Effect of compaction pressure on sintered density of Al–Pb/fly-ash composites sintered at 500 °C

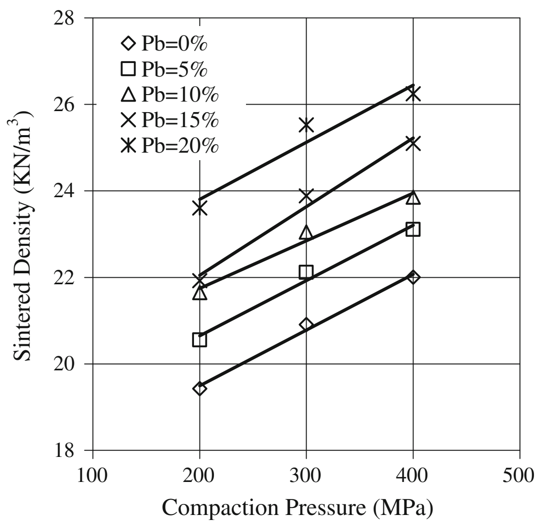

Fig. 6 Effect of compaction pressure on sintered density of Al–Pb/fly-ash composites sintered at 530 °C

4.5 %Cu-15 %Pb materials by powder metallurgy technique. The compacting and sintering characteristics of Al/fly-ash composites were reported by Guo et al. [9]. Seelam et al. [10] studied the compacting characteristics of Al–Pb/fly-ash composites. This paper deals with the preparation of Al–Pb/fly-ash composites by powder metallurgy technique and study of their sintering characteristics.

2 Experimental Details

The materials used in the present investigation were powders of Al, Pb and fly-ash. Al powder was procured from M/s S.D.Fine Chemicals Limited, Mumbai-India and Pb powder was procured from M/s Lobo Chem, Mumbai-India. The specifications of these powders were shown in Table 1. Fly-ash was collected from Dr. Narla Tata Rao Thermal Power Station, Ibrahimpatnam, Andhra Pradesh, India. Powder mixtures containing Al-10 wt% Fly-ash with 0, 5, 10, 15 and 20 wt% Pb were prepared and blended in a

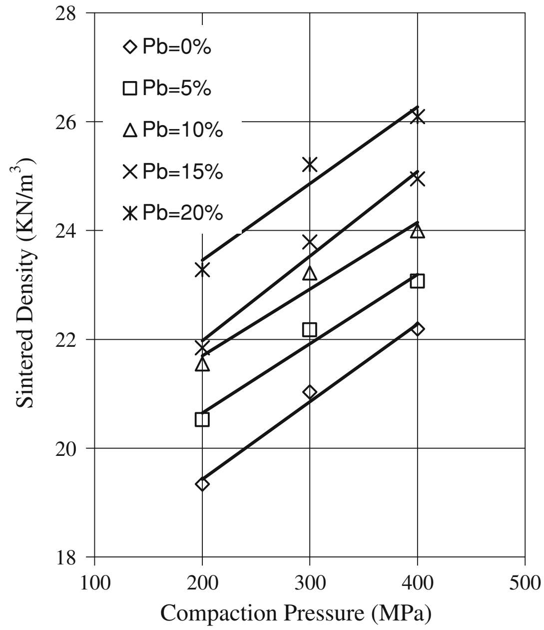

Fig. 7 Effect of compaction pressure on sintered density of Al–Pb/fly-ash composites sintered at 560 °C

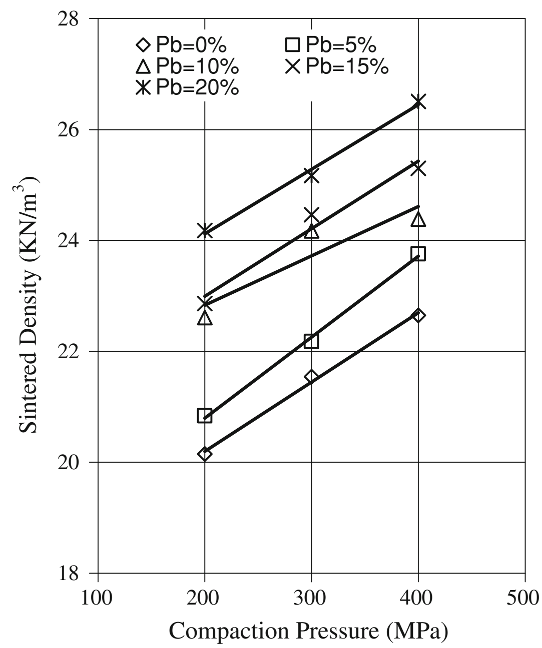

Fig. 8 Effect of compaction pressure on sintered density of Al–Pb/fly-ash composites sintered at 590 °C

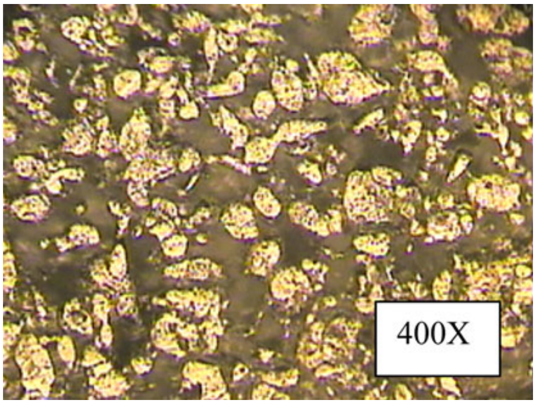

Fig. 9 Microstructure of Al-5 wt% Pb/10 wt% fly-ash composite compacted at 200 MPa and sintered at 500 °C

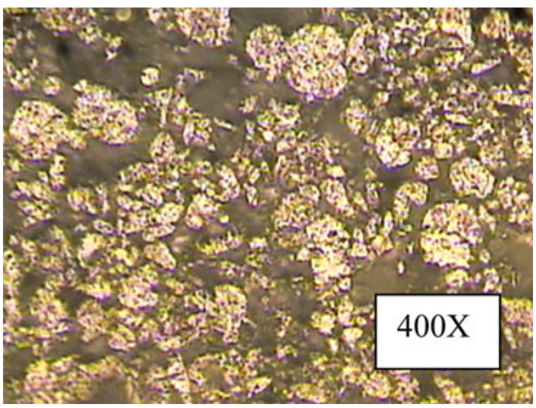

Fig. 10 Microstructure of Al-5 wt% Pb/10 wt% fly-ash composite compacted at 300 MPa and sintered at 500 °C

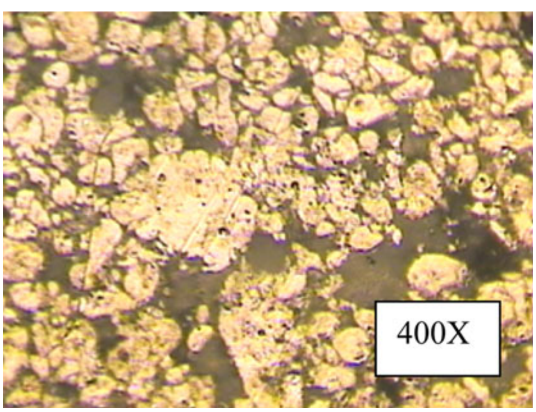

Fig. 11 Microstructure of Al-5 wt% Pb/10 wt% fly-ash composite compacted at 400 MPa and sintered at 500 °C

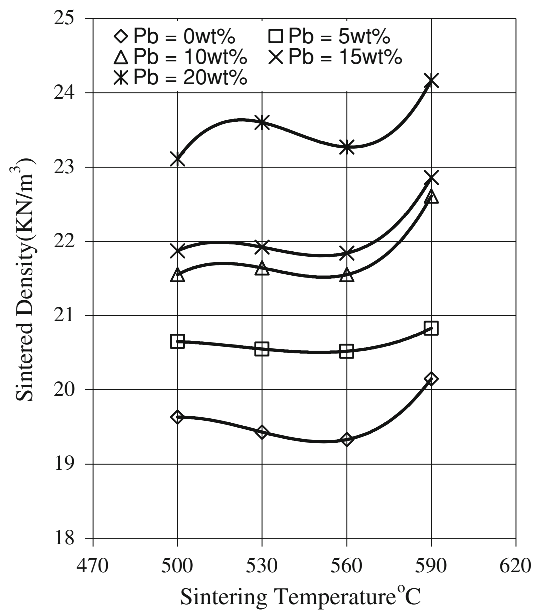

Fig. 12 Effect of sintering temperature on sintered density of Al–Pb/10 wt% fly-ash composites compacted at 200 MPa

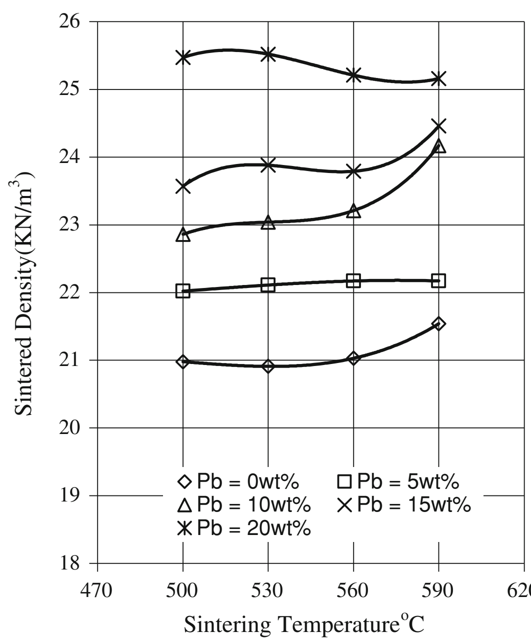

Fig. 13 Effect of sintering temperature on sintered density of Al–Pb/10 wt% fly-ash composites compacted at 300 MPa

suitable blender. These powder mixtures were compacted at 200, 300 and 400 MPa compaction pressure in a steel die into pellets of 9 mm diameter and 9 mm length using single action die. Silicone spray was used as die wall lubricant. The compacts were sintered at 500, 530, 560 and 590 °C in an argon gas atmosphere for duration of 45 min. Sintered density, hardness and strength of the compacts were evaluated as a function of sintering temperature, compaction pressure and wt% of Pb.

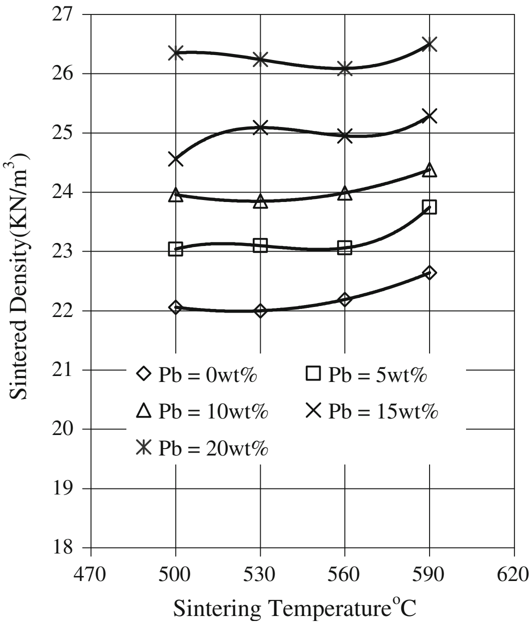

Fig. 14 Effect of sintering temperature on sintered density of Al–Pb/10 wt% fly-ash composites compacted at 400 MPa

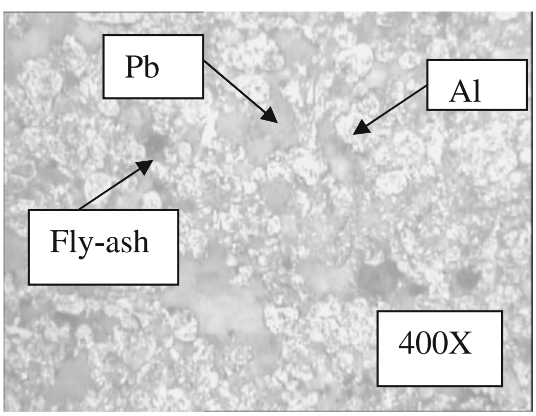

Fig. 15 Microstructure of Al-5 wt% Pb/10 wt% fly-ash composites compacted at 300 MPa and sintered at 500 °C

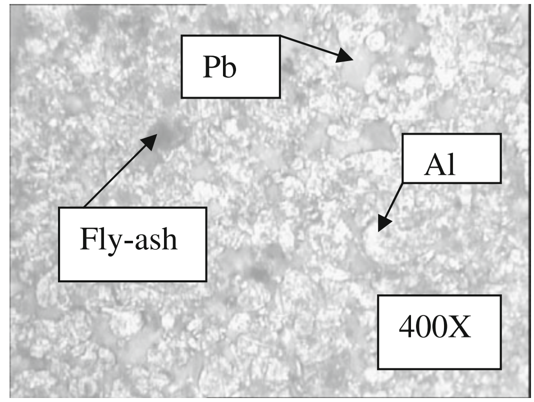

Fig. 16 Microstructure of Al-5 wt% Pb/10 wt% fly-ash composites compacted at 300 MPa and sintered at 530 °C

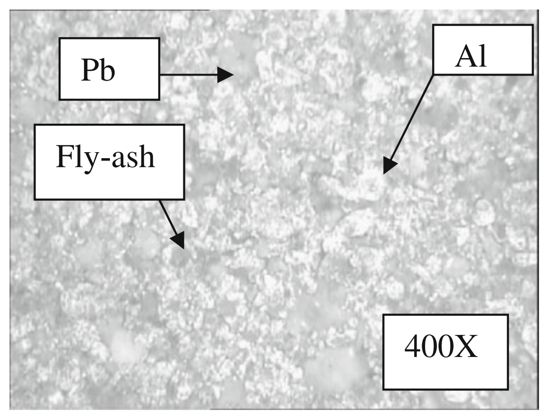

Fig. 17 Microstructure of Al-5 wt% Pb/10 wt% fly-ash composite compacted at 300 MPa and sintered at 560 °C

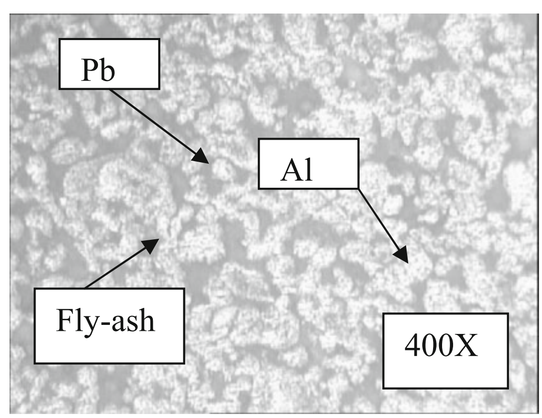

Fig. 18 Microstructure of Al-5 wt% Pb/10 wt% fly-ash composite compacted at 300 MPa and sintered at 590 °C

3 Results and Discussions

3.1 Powder Characteristics

The shape, size and size distribution of the individual powder particles is important in synthesizing the MMCs because it determines the final porosity and strength of the composites. The size distribution of the as received fly-ash particles determined by sieve analysis is shown in Fig. 1. It indicates that more than 90 % of fly-ash particles vary from 90 to 300 μm. The chemical composition of the fly-ash is shown in Table 2. The scanning electron microphotograph (SEM) of fly-ash powder representing its size and shape is shown in Fig. 2. This figure shows that, large numbers of fly-ash particles are in spherical shape with the particle size varying from 5 to 50 μm. Figure 3 shows the SEM photograph of Al particles, which indicates both rounded and elongated shape with the size varying from 3 to 50 μm.

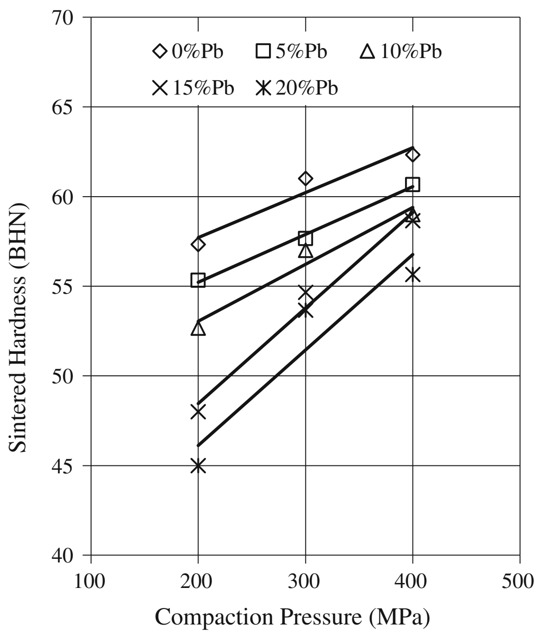

Fig. 19 Effect of compaction pressure on sintered hardness of Al–Pb/10 wt% fly-ash composites sintered at 500 °C

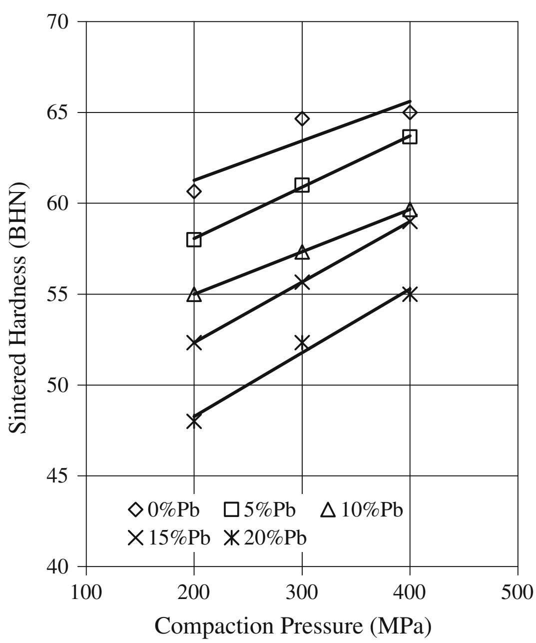

Fig. 20 Effect of compaction pressure on the sintered hardness of Al–Pb/10 wt% fly-ash composites sintered at 530 °C

Figure 4 shows near spherical shape for Pb particles with the size varying from 20 to 40 µm.

3.2 Sintering Characteristics

The effect of compaction pressure on the sintered density of the composites is shown in Figs. 5, 6, 7 and 8. For all the composites, and at all sintering temperatures, the sintered density increases with the increase in compaction pressure. This data also indicates that, the density increases with the increase in wt% of Pb. This is due to the higher density of Pb compared to that of Al and fly-ash. The increase in

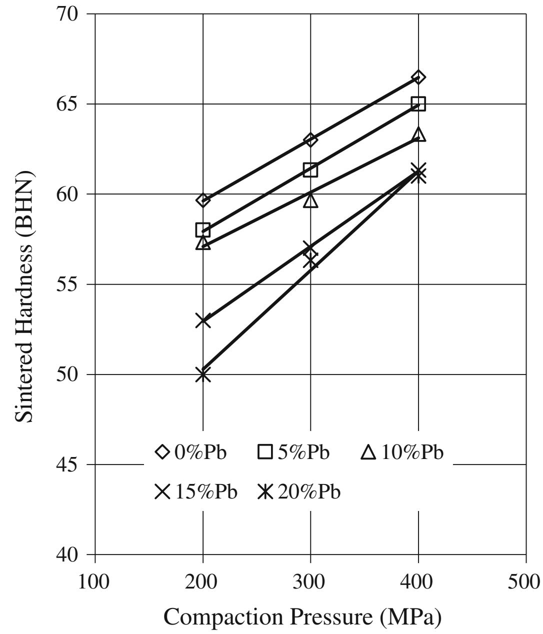

Fig. 21 Effect of compaction pressure on the sintered hardness of Al–Pb/10 wt% fly-ash composites sintered at 560 °C

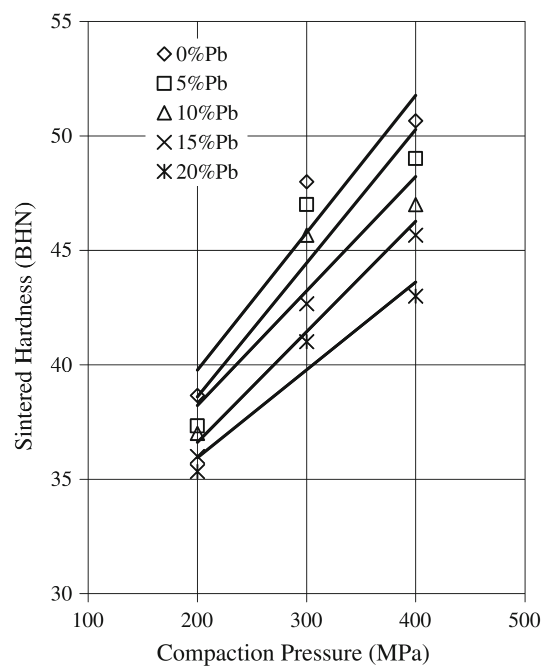

Fig. 22 Effect of compaction pressure on the sintered hardness of Al–Pb/10 wt% fly-ash composites sintered at 590 °C

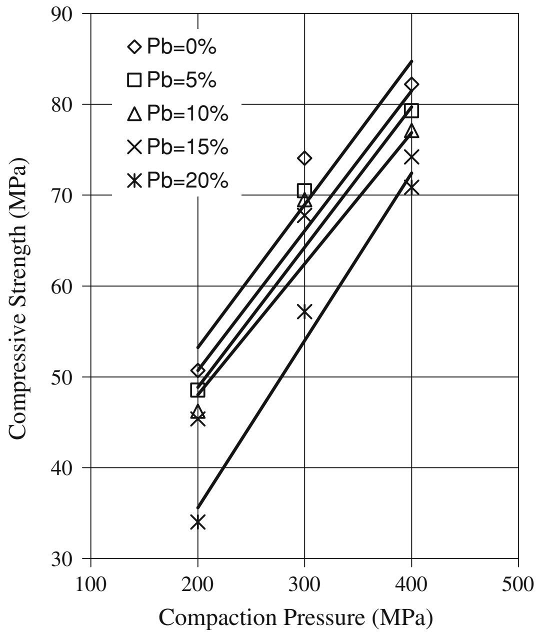

Fig. 23 Effect of compaction pressure on the sintered compressive strength of Al–Pb/10 wt% fly-ash composite sintered at 500 °C

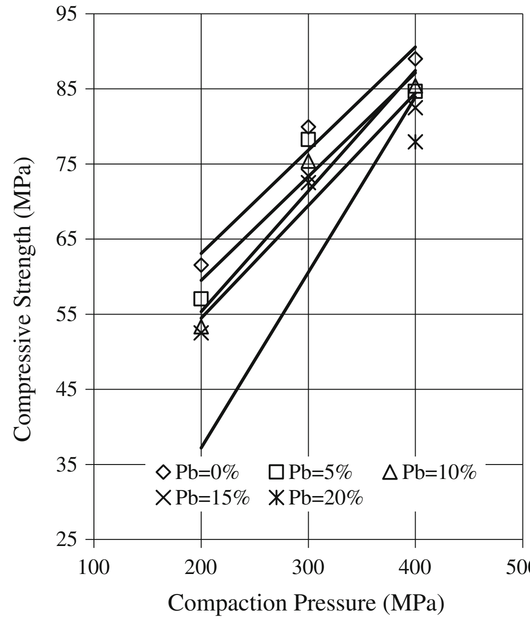

Fig. 25 Effect of compaction pressure on the sintered compressive strength of Al–Pb/10 wt% fly-ash composites sintered at 560 °C

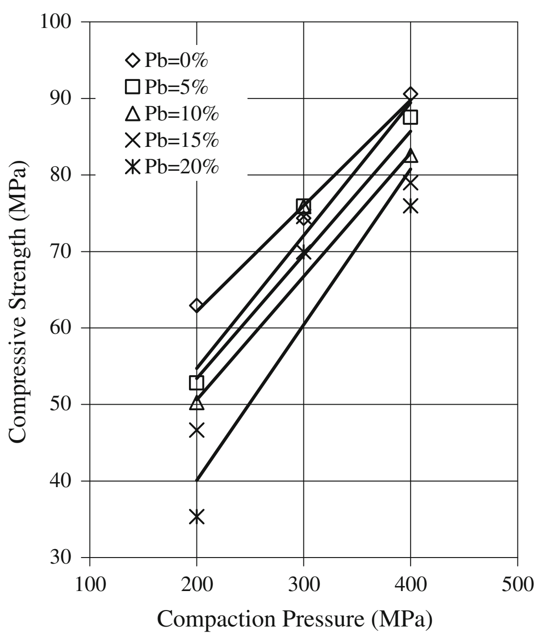

Fig. 24 Effect of compaction pressure on the sintered compressive strength of Al–Pb/10 wt% fly-ash composite sintered at 530 °C

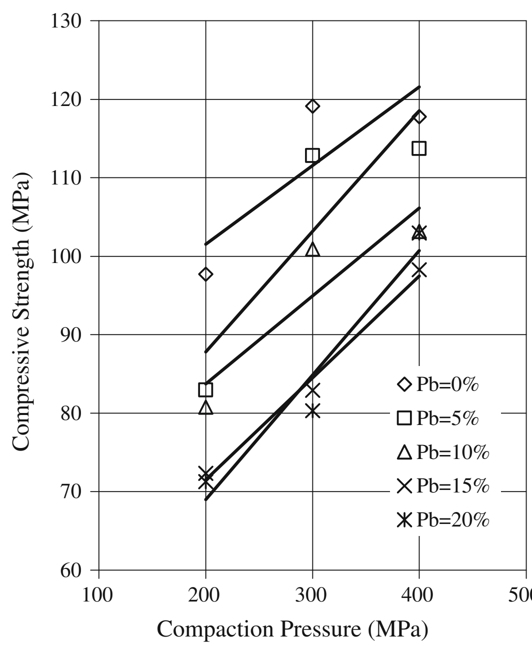

Fig. 26 Effect of compaction pressure on the sintered compressive strength of Al–Pb/10 wt% fly-ash composites sintered at 590 °C

sintered density with the increase in compaction pressure can be explained from better packing and closing of voids present in the green briquettes. With the increase in compaction pressure, the metallic particles (both Al and Pb) are plastically deformed and with closer packing the contact areas between the particles are increased which facilitates rapid diffusion and neck growth. The shrinkage of voids and densifications occurs by diffusion of vacancies. This can be clearly observed from the microstructures shown in Figs. 9, 10, and 11 for Al-5 wt% Pb/10 wt% fly-ash composites compacted at 200, 300 and 400 MPa and sintered at 500 °C.

The effect of sintering temperature on the sintered density is shown in Figs. 12, 13 and 14. The sintered

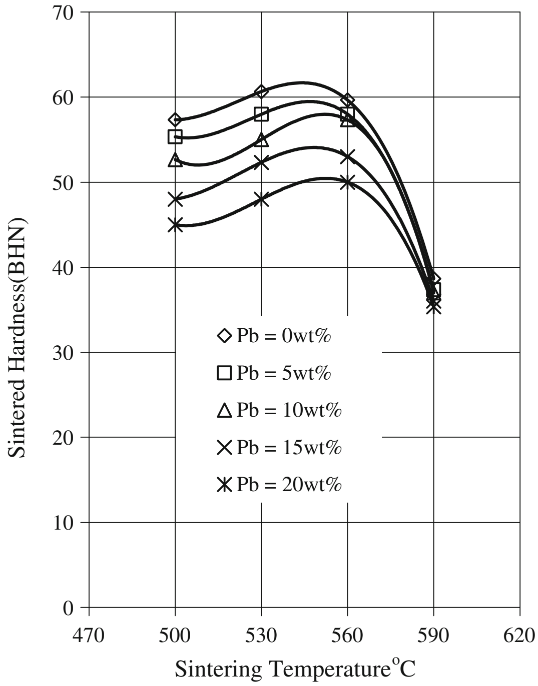

Fig. 27 Effect of sintering temperature on the sintered hardness of Al–Pb/10 wt% fly-ash composites compacted at 200 MPa

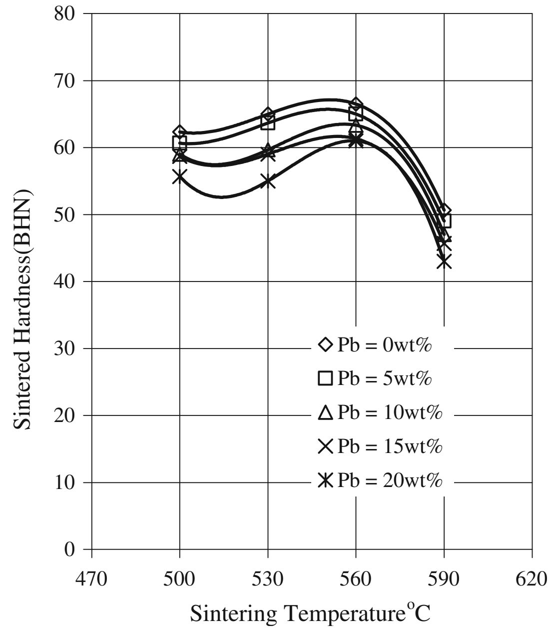

Fig. 29 Effect of sintering temperature on the sintered hardness of Al–Pb/10 wt% fly-ash composite compacted at 400 MPa

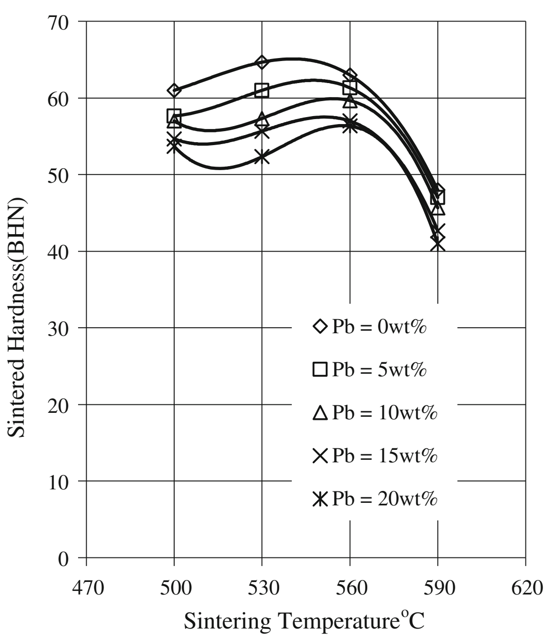

Fig. 28 Effect of sintering temperature on the sintered hardness of Al–Pb/10 wt% fly-ash composites compacted at 300 MPa

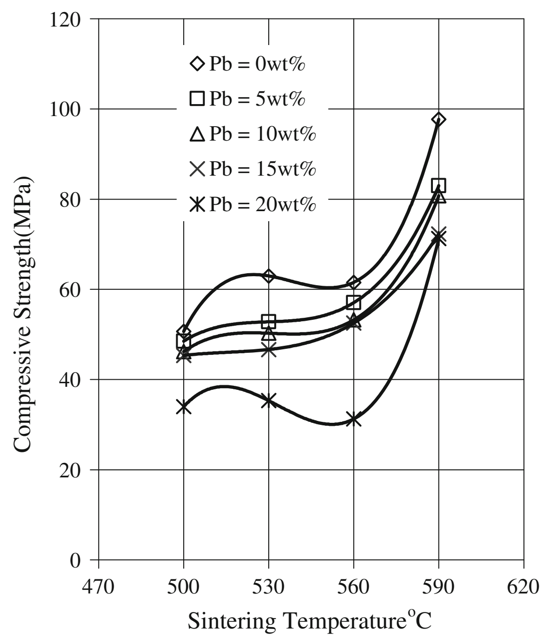

Fig. 30 Effect of sintering temperature on the sintered compressive strength of Al–Pb/10 wt% fly-ash composites compacted at 200 MPa

density almost remains constant in the temperature range of 500–560 °C and a slight increase is observed in the temperature range of 560–590 °C. At 590 °C a clear grain structure is observed compared to other sintering temperatures. In the temperature range of 500–560 °C the liquid phase sintering occurs due to melting of Pb. But at 590 °C, in addition to liquid phase sintering, the diffusion of Al particles takes place resulting in nucleation and development of new Al structure. This is well supported from the microstructure shown in Figs. 15, 16, 17 and 18.

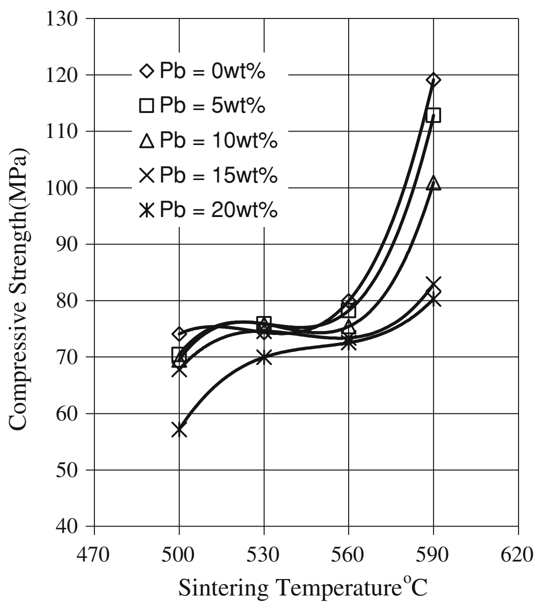

Fig. 31 Effect of sintering temperature on the sintered compressive strength of Al–Pb/10 wt% fly-ash composites compacted at 300 MPa

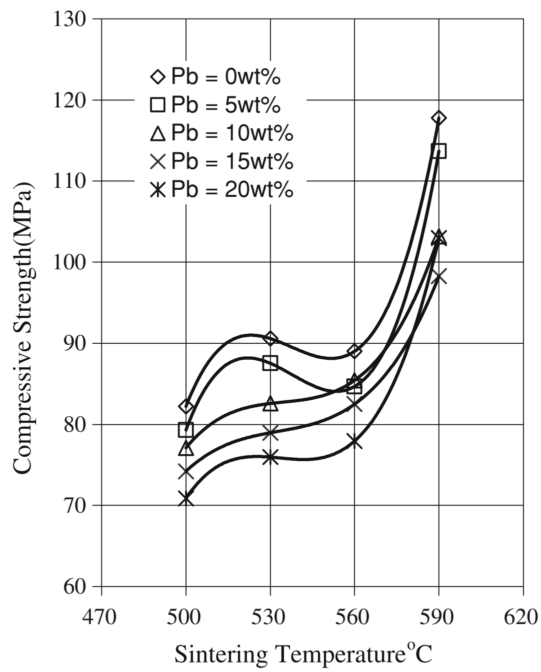

Fig. 32 Effect of sintering temperature on the sintered compressive strength of Al–Pb/10 wt% fly-ash composites compacted at 400 MPa

Figures 19, 20, 21 and 22 show the effect of compaction pressure on the sintered hardness. An increase in hardness is observed with the increase in compaction pressure. The sintered compressive strength increases with the increase in compaction pressure as shown in Figs. 23, 24, 25 and 26. With the increase in compaction pressure, the density increases leading to particle to particle bonding and interlocking of the particles increases. The increase in compaction pressure also increases the plastic deformation of Al and Pb particles which increases the strength and hardness. This can also be observed from the microstructures shown in Figs. 9, 10 and 11.

The effect of sintering temperature on the sintered hardness is shown in Figs. 27, 28 and 29. In the temperature range of 500–560 °C a marginal increase in hardness is recorded. This may be due to re-solidification of molten Pb at the interface between the Al and fly-ash particles. Beyond 560 °C the hardness decreases, which may be attributed due to formation of solidification contraction cavities in addition to stress relieving. This data also reveal a decrease in hardness with the increase in wt% of Pb, which is owed to increase in the soft phase (Pb).

A marginal change in the sintered compressive strength is observed in the temperature range of 500–560 °C and beyond 560 °C it increases. This is shown in Figs. 30, 31 and 32. At 590 °C the diffusion of Al particles is predominant and also solidified Pb forms as a continuous network at the grain boundaries leading to increase in strength. This can also be observed from the microstructures shown in Figs. 15, 16, 17 and 18.

4 Conclusions

1. The sintered density, hardness and compressive strength increases with the increase in compaction pressure.
2. With the increase in Pb content the sintered density increases where as the hardness and compressive strength decreases.
3. In the temperature range of 500–560 °C, the change in the properties is marginal but beyond 560 °C variation is observed.

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