International Journal of Engineering, Science and Metallurgy

(Full length research article)

Production and Study of Cast-Iron Dispersed Steel Matrix Materials

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Received 7 August 2012; accepted 15 August 2012, Available online 1Sept. 2012

Abstract

In the current work, mild steel nodular cast-iron (20 wt.% and 30 wt.%) powders were mixed together and then compacted by applying 800 MPa and 900 MPa pressure. Sintering was done at 1100 °C and time was varied from 20 to 150 min. Powders and powder-compacts were produced successfully. It was observed that, even before sintering, green compacts were sufficiently strong. The compacts were not crumbled into pieces even after impacting manually against the concrete floor. Microstructures were investigated by using optical microscope. Neither graphite nodules nor pearlite lamellae were observed in the sintered compacts. It was found that increasing sintering time increases hardness. Sintering process increases the compressive strength of the compact to significant extent. On the basis of obtained results, the developed material can be suitable candidate for the ball-bearing applications.

Keywords: *Cast-iron, Heat-treatment, Metallurgy, Powder, Steel*

1. Introduction

Competitive and cost conscious industries demand for the cost effectiveness materials with appropriate mechanical properties. Aluminum, aluminum-alloys and aluminum-based composites have limitation due to their low modulus of elasticity. Titanium-based materials are promising in many applications (including bio-medical instruments) due to their superior mechanical and chemical properties [1, 2]. However, for heavy-duty applications, for example, automobiles, crane etc components, titanium alloys are still too expensive. Iron and its alloys are yet to be displaced as engineering materials from the top slot (in terms of volume of consumption) by polymers, ceramics, or other materials. Therefore, it is important to research these materials to improve their properties and widen their applications. Cast-irons and steels have their own advantages and disadvantages. Cast-irons have good hardness, wear-resistance and compressive strength while steels have good toughness and ductility. In this regard, the current work focused on production and study of cast-iron dispersed steel matrix materials. This can be achieved by using powder metallurgy route.

Powder metallurgy is one of the most promising methods for fabricating the materials which are otherwise not possible by any conventional route, like casting. This method can produce near-net shape, high quality and complex-geometry parts in an economical manner. In powder metallurgy, powders with specific attributes of size and shape are packed and then converted into a strong, precise, high performance shape [3]. This processing method involves four main steps: powder production, mixing, cold compaction and sintering. PM is a flexible manufacturing process to offer a wide range of new materials, microstructures, and properties [4]. Metal matrix composites (MMCs) that are produced by selecting the powders of appropriate materials possess significantly improved properties including high specific strength; specific modulus, damping capacity and good wear resistance compared to unreinforced alloys [5]. It must be noted here that composite materials evolve from the idea of combining two basically dissimilar materials with different physical and mechanical properties to arrive at a product whose final properties are superior to those of the individual components.

It is known that the mechanism of evolution of microstructure differs depending on the process route, and therefore, process route has influence on properties. Considering this concept, idea of this project was born. In the current work, powders of mild-steel and nodular cast-iron were produced. Effect of sintering-time, composition of powders and compaction pressure on mechanical properties were investigated.

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2. Experimental

First, mild-steel and nodular cast-iron blocks were annealed at 950 °C to soften them. Chemical composition of mild-steel was as follows: C: 0.16%, Mn: 0.30%, Si: 0.25%, S: 0.030%, P: 0.030%. The chemical composition of nodular cast-iron was as follows: C: 3.33%, Mn: 0.33%, Si: 2.91%, S: 0.010%, P: 0.012%, Cr: 0.02%, Mo: 0.01%, Al: 0.0118%, Cu: 0.14%, Pb: 0.022%, Ti: 0.0297%, B: 0.0001%, Ca: 0.0019%

Mild-steel powders were made by using mechanical method, i.e. hand filing (Fig. 1(a)). Nodular cast-iron blocks were broken into fine chips (see Fig. 1(b)) by plainer mill and then ball-milled to produce fine powder. Ball milling was done for 4 h. Optical microscope (make: Carl Zeiss image analyzer) was used to evaluate the particle shape. For the determination of particle size distribution *sieve analysis* was carried out on the British Standards automatic screen. A stack of four full height screens with a pan and a cover in the proper order was held between the base and the top plate of movable cage. A sample of 100 gm of metal powder placed on the top sieve and then, vibrated to provide circular and translating motions to the powders for duration of 15 min. The quantity of powder retained on each sieve was taken out and weighed accurately.

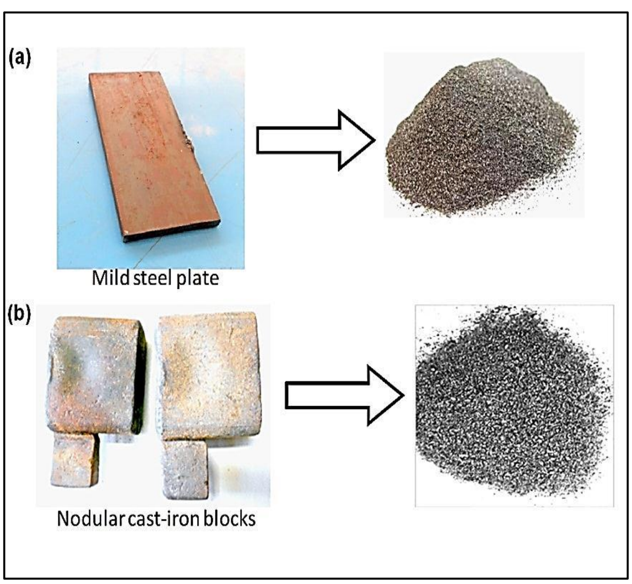

Fig. 1: (a) Mild steel plate into powder and (b) nodular cast iron blocks into powder

Mixing of the powders was done by manual shaking. Zinc-stearate (1.0 wt. %) was then added to the mixed metal powders for effective lubrication during compaction. The compaction die was made by oil hardening non-shrinkage (OHNS) alloy steel (this alloy is also known as AISI/SAE O1). The design of the die used for compaction is shown in Fig. 2. The powder-mixture was placed in the die cavity. Cold die compaction was carried out by using universal testing machine of 60 tons capacity. High pressure was exerted on the powders via vertically moving compacting punche (Fig. 2). The pressure applied was 800 MPa for three specimens and 900 MPa for one specimen (see Table 1). After ejection from the die, the compacts have sufficient strength (green strength) to withstand further handling without any damage. In fact, the green compacts were able to withstand the intentional manual impact on a concrete floor. This ensures the successful compaction of the powders.

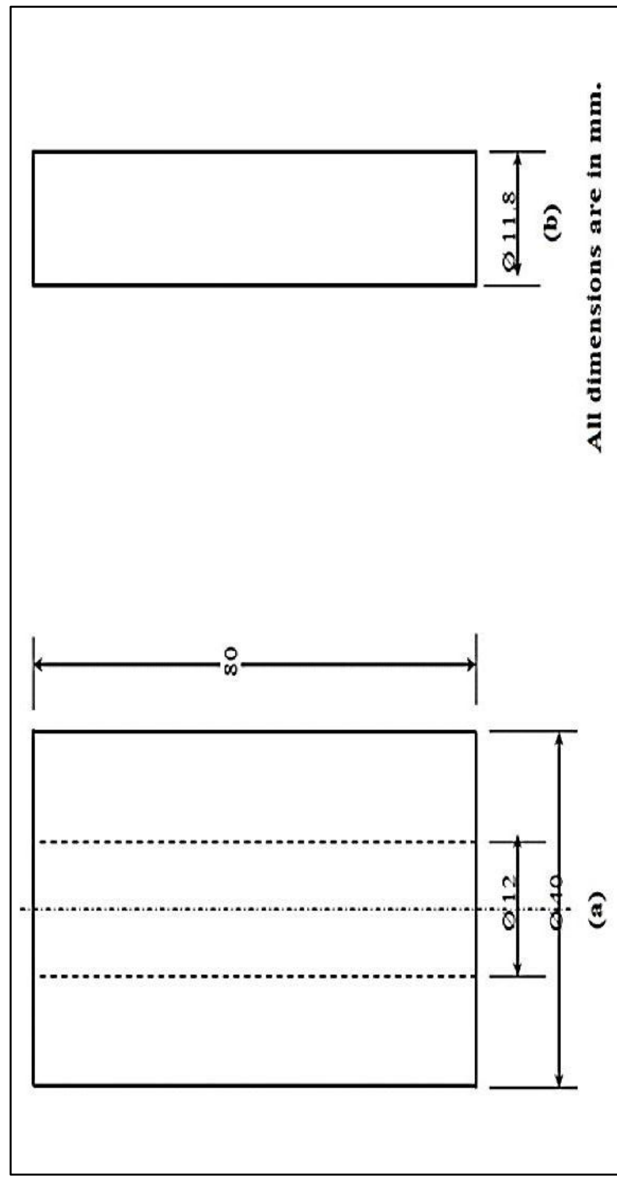

Fig. 2: Design with dimensions of (a) compaction die and (b) punch

Table 1: Experimental parameters used for making cast-iron dispersed steel matrix specimens

Material designation	Mild steel powder(wt. %)	Nodular cast-iron powder (wt. %)	Compaction pressure (MPa)	Sintering temperature(± 30 °C)	Sintering time (Min)
A	80	20	800	1100	20
B	80	20	800	1100	40
C	80	20	800	1100	60
D	70	30	900	1100	150

Sintering was carried out in muffle furnace. The temperature for sintering was 1100 °C ± 30°C and time was varied from 20 min to 150 min. The components were kept in a specially prepared arrangement to prevent the components from oxidation during sintering. A crucible type arrangement was made by welding a section of cylindrical pipe and two steel plates, one for bottom support and other for top cover. Interior of the cylinder was divided into four sections which were filled with alumina powder. The components are kept in alumina bed. The alumina particles easily facilitate the heat transfer to components to be sintered and prevent them from oxidation.

The sintered compacts were investigated using optical microscopy, hardness measurements and compression testing. Optical microscopic analysis was done using Carl Zeiss microscope and image analyzer. As usual carefully prepared specimens were grinded and polished using silicon-carbide emery papers. Final polishing was done on velvet-cloth polishing machine with intermittent application of fine suspensions of alumina to get better finish on polished surface. A freshly prepared 3 vol.% Nital was used as etchant. Rockwell hardness machine was used for measurement of hardness on B or C scale. The flat surface of specimen was prepared by using polishing paper. A minor load of 10 kg was first applied to seat the specimen. Then major load of 100 kg was applied for 15 sec and resistance to indentation was automatically recorded on the dial gauge. An average of three readings was reported. For compression testing the universal testing machine with 60 tones capacity was employed.

3. Results and discussion

Microstructures of annealed mild-steel and nodular cast-iron is shown in Fig. 3. Microstructure of mild-steel shows the ferrite (bright grains) and pearlite (dark grains). This is a typical microstructure of annealed mild-steel. The measured hardness of the mils-steel plates is about 67 HRB. Microstructure of the annealed nodular cast-iron shows the presence of graphite nodules in the pearlite/ferrite matrix. Size of the graphite nodules is in the range of 15-31 µm. The measured hardness of the annealed cast-iron blocks is about 55 HRB.

Understanding the particle shape of powders is an important step in powder metallurgy processing. Particle shape has a pronounced effect on the packing of powders and has an influence on its compaction and sintering properties, and hence, the mechanical strength of the sintered product. Fig. 4 shows the micrographs of mild-steel and nodular cast-iron powders. It is clear from the figure that the produced powders have irregular flaky shape and from Table 2, an average shape-factor =(Length of particle/Breadth of particle) of the mild-steel and nodular cast-iron powders are 1.22 and 1.14 respectively. Irregular flaky shaped particles have a reduced apparent density and flow rate, but have a good pressing and sintering properties [6].

Apart from the particle shape, particle size-distribution is also of fundamental importance because it affects the pressing and sintering behaviour as well as the physical and mechanical properties of the sintered material. By employing an appropriate particle size-distribution the inter-particle porosity can be minimized, i.e. densification can be increased. Therefore, with the help of its knowledge the properties of green and final product can be controlled. Fig. 5(a) shows the particle size-distribution of the mild-steel and nodular cast-iron powders. It is observed that the particle size ranges from 75 µm to 175 µm for the both alloy powders. Cumulative particle size-distribution graph (see Fig. 5(b)) shows that about 75% of the total powder produced for mild-steel and nodular cast-iron is having size of 100 µm or above. In other words, only small quantity, i.e. about 25%, of the powder is less than 100 µm size. Therefore, the powders used for further processing is in the range of 100-175 µm which facilitate optimum packing (with flaky particles) and optimum sinterability.

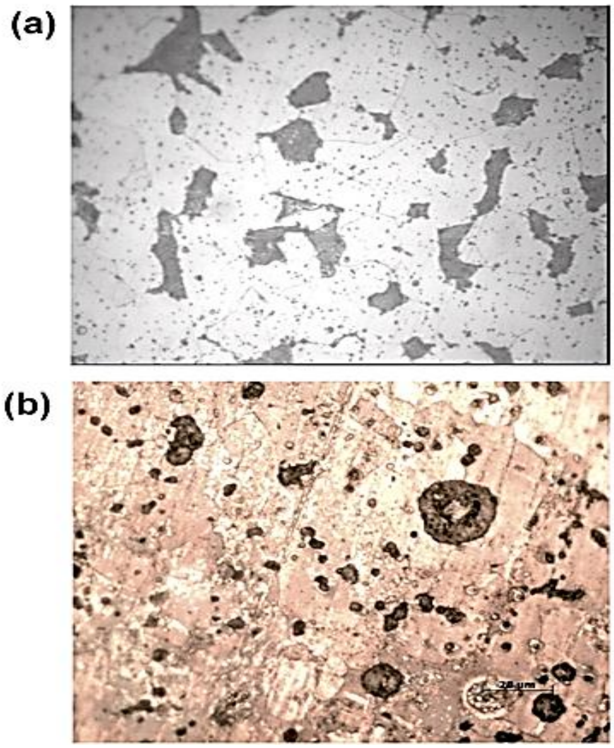

Fig. 3 Optical micrograph of annealed (a) mild-steel and (b) nodular cast-iron

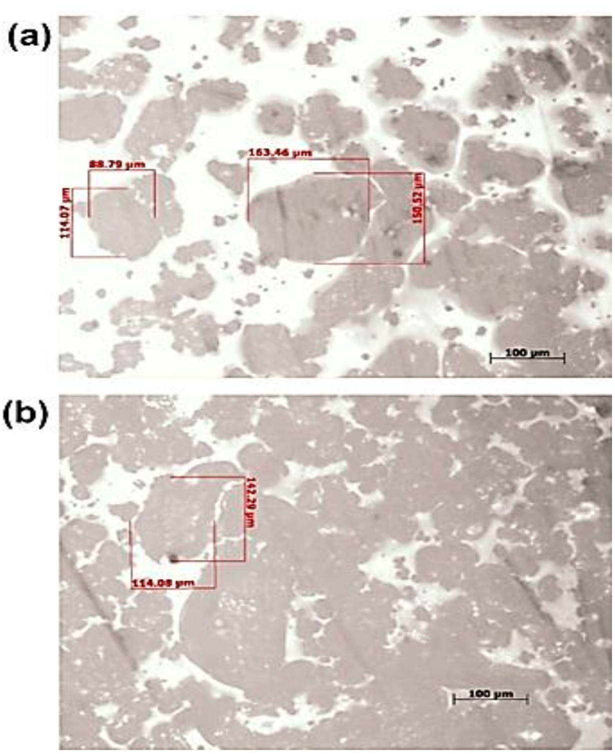

Fig. 4: Micrograph of (a) mild-steel powders and (b) nodular cast-iron powders.

Table 2 Powder particle dimensions and shape factors for mild-steel and nodular cast-iron.

Sr. No.	Powder	Length (µm)	Breadth (µm)	Shape factor	Average shape factor
1	Mild steel	163.46	150.52	1.08	1.22
		114.07	88.79	1.28	
		137.61	106.44	1.29	
2	Nodular cast iron	142.29	114.08	1.25	1.14
		125.65	124.65	1.01	
		155.23	134.06	1.16	
		200.74	179.7	1.17	

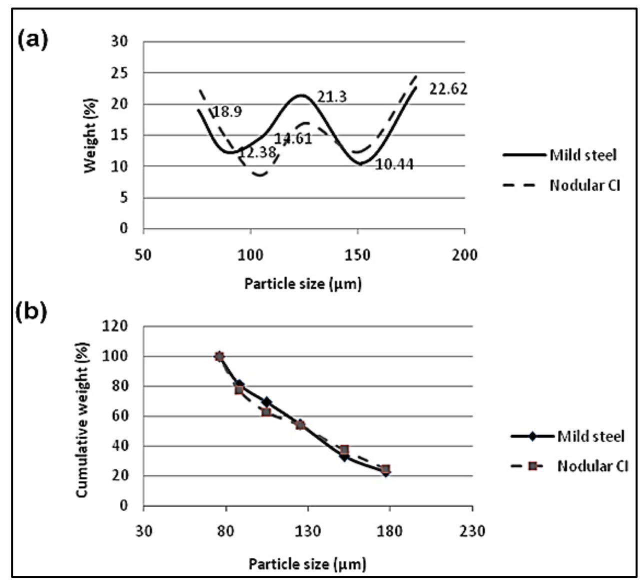

Fig. 5: (a) Particle size-distribution and (b) cumulative particle size-distribution obtained by sieve analysis of mild-steel and nodular cast-iron powders

Fig. 6 shows the optical micrographs of the green compact (i.e. non-sintered compact) of mild-steel and 20 wt.% nodular cast-iron powders compressed at 800 MPa. Fig. 6(a) is obtained at low magnification (100X) and Fig. 1(b) is obtained at higher magnification (500X) of optical microscope. Fig. 1(b) is the micrograph of a single powder particle. At lower magnification, powder particles of about 100-175 µm are observed clearly. However, at high magnification crack-like structure is visible, which is indicated by arrows in Fig. 6(b)), within the powder particle. This indicates that during compaction at high pressure, the powder particles are broken into small pieces. But, due to the plastic deformation, these pieces are mechanically bonded together.

Optical micrographs of the sintered compacts of mild-steel and 20 wt.% nodular cast-iron powders which are compressed at 800 MPa and sintered at 1100 ± 30 °C for 20-60 min are shown in Fig. 7. All micrographs are obtained at the same magnification of optical microscope. Darker patches seen in the micrographs are associated with the porosity. As the sintering time increases, porosity in the compacts decreases and the grain size increases. This gives an indication of the more densely packing of the powder particles due to the diffusion phenomenon. Bonding between powder particles requires transport of material from their inside to points and areas where they are in contact with one another [6]. Pore-rounding and pore-shrinkage require transport of material from the dense volume to the pore surfaces, as well as from softer to sharper corners of the pore surface [7]. The powder particles come much closer with increase in the sintering time. However, prolonged sintering time causes coarsening of the powder particles. But, hardness results shown in Table 3 indicate that the sintered compacts become harder with increasing sintering time. This behaviour is possibly due to the enhanced densification of the powder compacts at longer sintering-time.

It is mentioned in Section 2 that the green compacts were able to withstand the intentional manual impact on a concrete floor. Even though this is true, sintering process is very useful in enhancing the strength of the compacts. The compressive strength of the green compact made-up of mild-steel and 30 wt.% nodular cast-iron powders (specimen D) is about 244 MPa. Sintering at 1100 °C for 150 min increased the strength of the same compact to 2616 MPa. Compressive strength of the specimen B is also observed to be high, i.e. 2462 MPa. This behaviour confirms that sintering is crucial in improving the load bearing capacity of the compacts.

On the basis of obtained results, the sintered compact of mild-steel and nodular cast-iron can be the suitable candidate for ball-bearing applications. The possible advantages of the material are as follows: (i) high hardness (which is needed for good wear resistance), (ii) good compression strength (therefore, good load bearing capacity), (iii) presence of porosity even after sintering (which are useful for retaining lubricants, like oil), (iv) any shape can be given to the compacts by using appropriate die design.

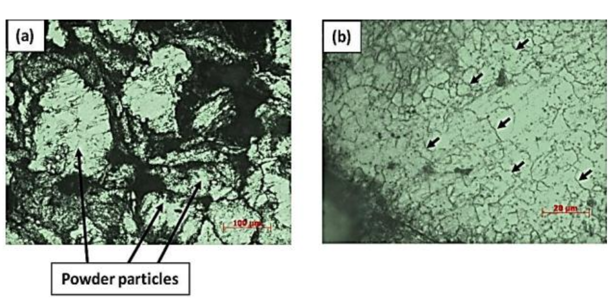

Fig. 6: Optical micrographs of the green compact of mild-steel and 20 wt.% nodular cast-iron powders compressed at 800 MPa obtained at (a) 100X and (b) 500X magnification of optical microscope.

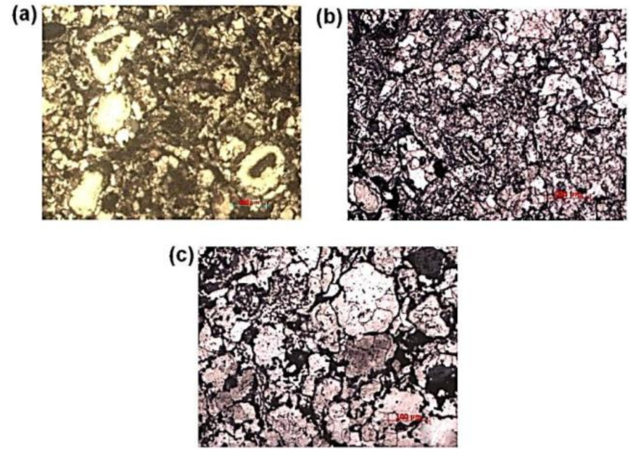

Fig. 7: Micrographs of mild-steel and 20 wt.% nodular cast-iron powder compacts compacted at 800 MPa and sintered at 1100 ± 30 °C for (a) 20 min, (b) 40 min and (c) 60 min. All micrographs are at 100X magnification of the optical microscope.

Table 3: Hardness of the annealed mild-steel, annealed nodular cast-iron and powder compacts

Material designation	**Mild steel powder (wt. %)**	**Nodular cast-iron powder (wt. %)**	**Compaction pressure (MPa)**	**Sintering temperature(± 30 °C)**	**Sintering time (Min)**	**Hardness(HRB)**
Nodular cast-iron (annealed)	-	-	-	-	-	55
Mild steel (annealed)	-	-	-	-	-	67
A	80	20	800	1100	20	46
B	80	20	800	1100	40	65
C	80	20	800	1100	60	73
D	70	30	900	1100	150	78

Conclusions

- Mild-steel and nodular cast iron powders were successfully produced by mechanical method of hand-filling, machining and grinding. The produced powders had irregular flaky shape and the average shape-factor of the mild-steel and nodular cast-iron powders were 1.22 and 1.14 respectively. Sieve analysis confirmed that the powders were in the size-range of 75-175 µm and 75% of the total quantity of powders was in the size-range of 100-175 µm.

- Porosity in the sintered compacts decreased and the grain size increased with increase in the sintering time. This cased more dense packing of the powder particles. Therefore, the sintered compacts became harder with increasing the sintering time.

- Sintering process was very useful in enhancing the compressive strength of the compacts. The compressive strength of the compact made-up of mild-steel and 30 wt.% nodular cast-iron powders was improved from 244 MPa (non-sintered condition) to 2616 MPa (sintered condition).

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