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Characterization of pre-alloyed tin bronze powder prepared by recycling machining chips using jet milling

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ABSTRACT

In this study jet milling has been used as a novel method to recycle bronze machining chips into bronze powder suitable for making powder metallurgy components. This method has been compared with ball milling process to make an assessment of its efficiency as a recycling route. The size reduction rate, morphological, physical and mechanical properties of the bronze powders produced was investigated. It was found that, jet milling was a much less time consuming method compared to ball milling to pulverize bronze machining chips. The oxygen content of the ball milled product was increased during ball milling and reached 0.58% after 24 h while, the Jet milled powder was approximately free of oxides. In addition, jet milling produced powders with irregular shape and low work hardening compared to ball milled powders and hence better green properties for the former were observed. Although, for the ball milled powders only at 700 MPa compacts with adequate handling properties could be made, it was possible to make sound compacts of the jet milled powders at all the compacting pressures used and green density of 6.5–8 g/cm^3 was achieved by increasing the compaction pressure from 200 to 700 MPa.

1. Introduction

Tin bronzes (90% Cu and 10% Sn) are suitable bearing materials due to their good wear properties under corrosive conditions, high temperatures and high loads [1,2]. The bearing bronzes are usually continuously cast as bar or tube and machined into bushes, washers or other bearing components [3]. Machining of metals, results in the formation of large quantities of chips [4]. The large amount of loss of the starting material requires economical ways to recycle the chips. During the recycling of the waste by re-melting a considerable amount of the metal is lost as a result of oxidation. In addition, the cost of labor and energy as well as the expenditures on environment protection raise the overall cost of the manufacturing processes [5,6].

In recent years, solid state recycling processes have been suggested to recycle metallic scarps [7]. A number of valuable studies relating to the solid phase recycling and reusing of scrap materials have been reported, these studies are focused mainly on Aluminum [5–7], Titanium [8], magnesium [9,10]and Ferrous alloys [11–14].

One method of solid phase recycling of metal chips is pulverization to produce metal powders to make sintered components [8,11–14]. In many of the cases ball milling has been the main method used to convert machining chips into metal powders [12–14]. It has been known that, during the ball milling process powders are extensively work hardened [8,15]. Annealing of the produced powders has always been essential to relieve strain hardening and reduce surface oxides in order to improve compressibility of the powders [4,13–14].

As a pulverization technology, jet milling has significant advantages compared to ball-milling in preparing micro-sized particles. The strong points of jet milling includes; the absence of contamination, low wear rate, low noise, and the ability to pulverize heat sensitive materials [16,17]. In a jet mill the particles of the feed material are accelerated by a pressurized gas and size reduction is achieved either by impact on a target plate or through mutual collisions of the accelerated particles [18–20]. Jet mills have been used widely in the chemical, pharmaceutical and mineral industries [16–18,20–22] however, according to the knowledge of the present authors there are very limited studies on the use of jet milling to produce metallic powders.

Recently Emadi et al. [11] employed target jet milling to convert grey cast iron chips into powder and used it successfully to produce sintered powder metallurgy parts. Xin Lu et al. [19] conducted a detailed study on preparation and characterization of TiAl alloyed powders using fluidized bed jet milling from the pre-crushed ingot. Rama Rao and Hadjipanayis [23]studied the effect of jet milling conditions on particle size and magnetic properties of MnBi alloy.

Among metallic powders bronze powder has wide application in production of sintered porous bearings as well as structural parts [24, 25]: Therefore, converting bronze machining chips into powder could be a valuable solution for recycling bronze scraps. In this work for the first time a comparative study was done on pulverization of tin bronze machining chips using ball milling and jet milling processes. An experimental target plate jet milling device was designed and used to produce powder from tin bronze chips and in case of ball milling, a lab scale

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Table 1
Chemical composition of the tin bronze alloy.

Element	Sn	Zn	Pb	P	Fe	Al	Cu
Weight percent	10.4	0.75	0.1	0.003	<0.005	0.01	Base

conventional ball mill was used for pulverization of the same. The size reduction rate and the morphological properties of particles were investigated as well as the physical and the mechanical properties of the bronze powders produced using the two different methods of pulverization.

2. Material and methods

The material used in this study was a tin bronze alloy machining chips with the chemical analysis according to the Table 1. SEM image and microstructure of machining chips are shown in Fig. 1. The microstructure consists of: a copper-rich solid solution of tin in copper (alpha matrix) and a eutectoid which contains alpha and delta phases, the latter being an inter-metallic compound with a fixed composition [26]. The size distribution of initial machining chips was 20–30 mesh (595–841 μm).

Ball milling and target plate jet milling were used to pulverize the machining chips. A lab scale ball mill with tool steel balls was used with a ball to material ratio of 20:1. The ratio of the balls to the material was chosen according to the most sited values in the literature. The rotational speed of ball mill was chosen by pre-experiments and optimum value was found based on maximum size reduction efficiency. This variable was optimized at 60 rpm which was equivalent to 74% of the critical speed. Milling was carried out for 4, 8, 16 and 24 h in order to follow the trend of pulverization.

In the case of jet milling, a target plate jet mill device was designed and used for the jet milling experiments. A vibratory feeder transported the chips into the mixing section which were then accelerated by a nozzle and impacted on to a target inside the grinding chamber. Schematic illustration of the equipment is shown in Fig. 2. The operational parameters of jet milling were kept constant on their optimum value found by pre-experiments, i.e. a feed rate of 5 g/s, a pressure of 6 bar, a nozzle to target distance of 8 cm and impact angle of 90°. After each impact cycle, the content of the chamber was carefully collected for investigation. The aim of this work was the characterization of recycled bronze powder prepared by jet milling and ball milling processes: Therefore, all of the milling parameters were kept the same on their optimum value throughout the experiments.

Scanning electron microscopy was used to study the morphology of the powders. The shape and morphological characterization of particles are based on the analysis of the particles or their projections [27]. In this study calculation was done from the particles silhouette and the mean values of about 100 particles were reported. The maximal (F_{max}) and minimal (F_{min}) diameter of projected particles were measured. From these basic measurements and calculations, shape factors given in the Eqs. (1)–(3) were used for the shape characterization of the particles.

$$\text{Elangation (E)} = \frac{F_{max}}{F_{min}} \tag{1}$$

$$\text{Circularity (Ci)} = \frac{P^2}{4\pi A} \tag{2}$$

$$\text{Equivalent diameter(Deq)} = 2\left(\frac{A}{\pi}\right)^{\frac{1}{2}} \tag{3}$$

where P and A are the silhouette perimeter and area, respectively [21].

The oxygen content of the powders was determined by subjecting a sample of the powder to hydrogen gas under the temperature of 875 °C and for a time period of 30 min and the resulting loss of weight, was measured according to ASTM E 159[28].

Phases were determined by X-ray diffraction (XRD) using filtered CuKα radiation ($\lambda = 0.15406$ nm). Internal strain of the powders was also calculated from broadening of XRD peaks using the Williamson-Hall method [29]

$$B\cos\theta = \frac{K\lambda}{d} + 2\varepsilon\sin\theta \tag{4}$$

where θ is the Bragg diffraction angle, d is the average crystallite size, ε is the average internal strain, λ is the wavelength of the radiation used, K is a constant with approximate value of 0.9, and B is the diffraction peak width at half maximum intensity. The average internal strain was estimated from the linear slope of Bcosθ versus 2sinθ. The effect of work hardening was also assessed by microhardness measurements.

In order to evaluate compressibility of the powders and to consider the green properties of the compacts, rectangular specimens were prepared according to ASTM B312 [30]. Compaction pressures of 200, 300, 400, 500, 600, and 700 MPa were used. Die walls were lubricated using zinc stearate dissolved in acetone to promote compaction and ejection from the die. The green samples were weighed with an uncertainty of ±0.01 g and their sizes were measured by a micrometer. The compressibility was determined by the determination of densities for each compaction pressure. The green strengths of the compacts were calculated using the formula:

$$S = \frac{3PL}{2Wt^2} \tag{5}$$

where S is the green strength in MPa, P is the force at the instant of the failure in N, L is the distance between the supports in mm, t is the

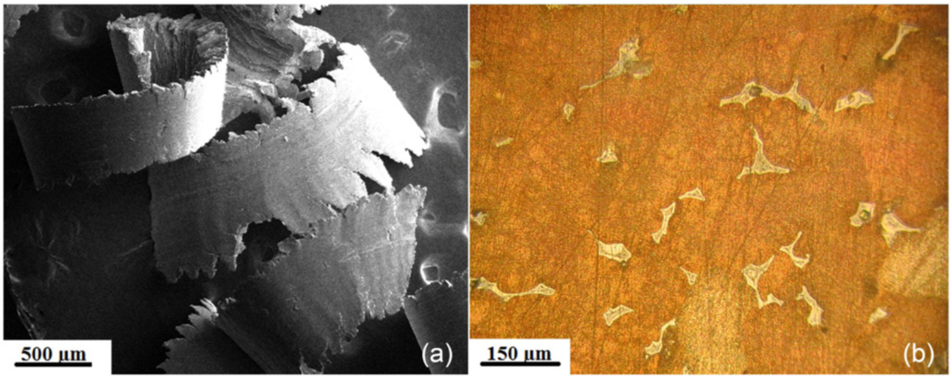

Fig. 1. (a) SEM image of initial machining chips (b) microstructure of the initial machining chips.