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Research Paper

Analysis of compressibility behavior and development of a plastic yield model for uniaxial die compaction of sponge titanium powder

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ABSTRACT

Uniaxial die compaction of Sponge Ti with a maximum particle size of 3 mm and irregular spongy particle morphology was conducted with the Gleeble® 3500 thermal-mechanical simulation testing system at room temperature. The compressibility behavior of the powder was studied using the Heckel equation. It was observed that the behavior of the material could be analyzed in two compaction pressure regimes. In the low pressure regime (<100 MPa) the powder exhibited high compressibility, while; in the high pressure regime (>100 MPa) lower compressibility of the Sponge Ti was observed. A pressure-dependent plastic yield model was employed to develop the yield criterion of the powder. In this model both geometric hardening of the powder and strain hardening of the incompressible material was considered. The model was validated by comparing the experimental and modeled results.

1. Introduction

Enhancement of the fuel economy is a continual challenge of the automotive industry. One effective approach to achieve better fuel economy is reducing the weight of the cars. Cui et al. (2011) reported that 57 kg weight reduction in a car results in 0.09–0.21 km per liter fuel economy improvement. Therefore, lightweight structural metals such as titanium are being sought to replace higher density steel parts. Titanium possesses a combination of attractive properties such as low density, high specific and fatigue strength, excellent fracture toughness, outstanding corrosion resistance and superior strength at high temperatures (Muhammad et al. (2014)). In addition Chunxiang et al. (2011) and Mallick (2012) reported some titanium alloys exhibit excellent oxidation resistance at elevated working temperatures up to 700 °C. This behavior makes these alloys a suitable candidate for high service temperature automotive parts such as the exhaust system, as reported by Kosaka et al. (2004).

Despite superior properties of titanium, high production costs are an obstacle to widespread adoption in a variety of applications. Froes et al. (2004) showed that the cost of titanium ingot in the automotive industry is 7.5 times higher than magnesium, 6.4 times higher than aluminum and 30 times higher than steels counterparts. In the form of sheet metal, these numbers are 2–5.5, 8–10 and 27–83 when comparing titanium to magnesium, aluminum and steel, respectively. One alternative way to produce low cost titanium parts is using powder metallurgy (PM) as a near-net-shape manufacturing process (Lou et al. (2014)). Chen et al. (2011) reported that PM can reduce the production costs of the titanium parts by up to 50%, for both pure and alloyed titanium. The first step in a successful PM process is the proper compaction of the powder in which a green compact with uniform density and low defects is obtained (Qian (2010)). Such an achievement is dependent on the understanding of the consolidation behavior of the powder and how it is affected by process parameters. Uniaxial die compaction is a common experiment to study the effect of compaction pressure on the relative density of pressed powder compacts (Cooke et al. (2016)). The outcome of the die compaction process in the form of a relative density-pressure relationship is then employed to analyze the densification characteristics of the powder using a compaction equation.

In the current study, uniaxial die compaction of Alfa Aesar® Sponge Ti-99.9% was studied using the Gleeble® 3500 thermal-mechanical simulation testing system. The compaction behavior of the powder was analyzed and interpreted using Heckel compaction equation. The yield criterion and constitutive behavior of the powder was developed and validated using a pressure-dependent plastic yield model.

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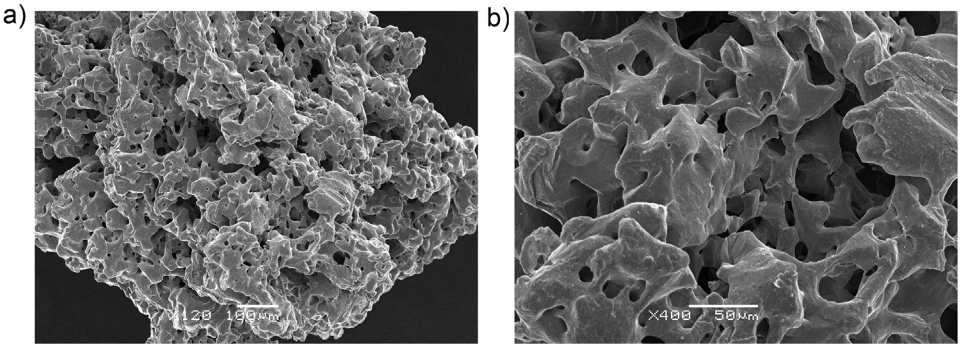

Fig. 1. SEM image of the morphology of Sponge Ti powder.

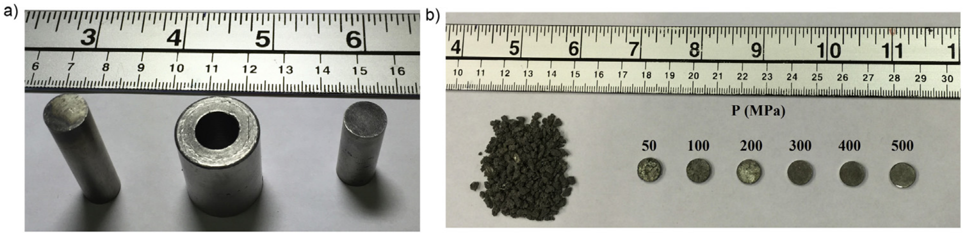

Fig. 2. (a) Cylindrical die and metallic rods used for powder compaction and (b) loose powder and compacts produced under various compaction pressures.

Table 1
Chemical composition of Sponge Ti (ppm) reported by the supplier.

Element	Amount	Element	Amount
Al	0.340	Ni	<0.050
Co	<0.050	Sb	0.200
Cr	0.070	Sn	0.300
Cu	0.250	V	0.460
Fe	26.500	Zr	1.310
Mn	0.940	O	735.00
N	13.000		

2. Experiments

The powder used for the current investigation was Alfa Aesar® Sponge Ti-99.9% with a maximum particle size of 3 mm (Lot No. K05Y023). Table 1 shows the chemical composition of the Sponge Ti, including the level of any impurities. Fig. 1 shows the SEM image of the Sponge Ti morphology. This powder possesses irregular particle morphology with interconnected porosities.

Uniaxial die compaction of the Sponge Ti was carried out using a Gleeble® 3500 thermal-mechanical simulation testing system at room temperature (Gleeble® is a trademark of Dynamic Systems, Inc., Poestenkill, NY, USA). Conduction of the compaction using the Gleeble machine is beneficial as it allows for precise control of both the strain rate and total strain experienced by the powder. The cylindrical die used for compaction was made from hardened tool steel with the inner diameter of 9.5 mm. Two metallic rods were used as punch to compact the powder. First, a metal rod was placed inside the die and then the powder was placed in the die cavity followed by placing the second rod on top of the powder. The whole set-up was then placed inside the Gleeble machine to conduct the cold compaction. Compaction pressure (P) was varied between 10 and 550 MPa and each compaction trial was completed in 50 s to ensure a consistent compaction time. Fig. 2(a) shows the cylindrical die and punches used for powder compaction and Fig. 2(b) depicts the loose powder and compact discs after compaction.

The dimensions and weight of compact discs were measured after compaction to calculate the green density. Optical microscopy (OM) and Vickers microhardness test with the load of 0.5N were employed to analyze and characterize the compacts. For each sample, at least 10 microhardness tests were performed.

3. Results

3.1. Compaction behavior

The compaction behavior of the Sponge Ti powder is shown in Fig. 3. Similar to other conventional powders, the consolidation behavior of Sponge Ti was directly affected by the compaction pressure; i.e. higher relative density (R) was obtained by increasing the compaction pressure. At $P = 0$ MPa, where the loose powder is under no pressure, the relative density of the powder is equivalent to the tap density (R_T). For the Sponge Ti, $R_T = 0.13$. By increasing the compaction pressure from 10 MPa to 100 MPa, a rapid powder consolidation was observed; the relative density rises from 0.28 to 0.57. Beyond the compaction pressure of 100 MPa, more gradual increase in the relative density was seen. At the highest compaction pressure (550 MPa), a maximum relative density of $R = 0.89$ was achieved.

To perform a comprehensive analysis on the compressibility of the powders, Panelli and Filho (2001) reported several compaction equations, developed based on the linear regression between the compaction pressure and the relative density. Amongst these analyses, Heckel compaction equation, developed by Heckel (1961), shown by Eq. (1), has been used widely in various studies.

$$\ln(\frac{1}{1-R}) = A_1 P + B_1 \tag{1}$$

where P is the compaction pressure (in MPa), R is the relative density ($0 < R < 1$), A_1 is a constant which represents the compressibility of the powder and B_1 is the y-intercept. The advantage of this compaction equation over other equations is the fact that the only required data for analysis is the compaction pressure and relative density. In Heckel equation, higher A_1 represents higher relative density for a given compaction pressure which implies higher compressibility. Fig. 4 shows the results of compressibility analysis of Sponge Ti using the Heckel compaction equation along with the compressibility parameters as the slope of the linear curve. To obtain better insight on the compaction behavior of Sponge Ti, a