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MECHANICAL PROPERTIES OF LCS POROUS STEEL: COMPARISON BETWEEN DISSOLUTION AND DECOMPOSITION ROUTES

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Abstract

This paper compares the mechanical properties of porous steels produced by the lost carbonate sintering (LCS) process between the decomposition and dissolution routes. The flexural strength, compressive strength and elastic modulus of the porous steel specimens produced either by the decomposition route or by the dissolution route increased with increasing relative density, pore size and compaction pressure. The specimens produced by the decomposition route were generally much stronger and stiffer than those produced by the dissolution route when the relative density was above 0.21, mainly because of the higher sintering temperature in the decomposition route. The specimens produced by combining dissolution and re-sintering were weaker than those produced by decomposition alone, likely because of the corrosion caused by the residual potassium carbonate left in the specimens due to incomplete dissolution.

Introduction

Porous metals are metals with pores deliberately integrated in the structure. The unique combinations of properties of porous metals cannot always be obtained with dense polymers, metals, ceramics, or polymer foams and ceramic foams. For example, the mechanical strength and stiffness of porous metals are much higher than those of polymer foams. Generally, they are more stable at high temperatures and in harsh environments than polymer foams. As opposed to ceramics, they have the ability to deform plastically and absorb energy [1]. Moreover, they are thermally and electrically conductive. When they have open cell porosity, they are permeable and have high specific surface areas. With these properties, porous metals have many potential applications.

Porous steels have been considered as an alternative to aluminum foams, because steel has higher strength, has higher capability to absorb energy and is generally cheaper than aluminum. However, the high melting temperature of steel makes low-cost production of foams a challenge. Most processes used to manufacturing porous steel are based on powder metallurgy instead of casting.

Sintered powder was the first commercially available porous metals used in engineering applications. Sintered powder has been used with success for the fabrication of filters, batteries and self-lubricated bearings since the 1920's [2]. However, its porosity and pore size can only be controlled by compaction pressure. The porosity is usually low and pore size is small and uncontrollable. The lost carbonate sintering (LCS) process, using carbonate grains as the space holder, is a versatile process for manufacturing porous metals [3, 4]. The porosity of porous metals can be controlled by the volume percentage of the carbonate and the pore size can be controlled by the size of the carbonate grains.

Potassium carbonate (K_2CO_3) is normally used in LCS, because it has low cost, low melting point and high water-solubility [5]. There are two routes to remove K_2CO_3 in the LCS process. The decomposition route removes K_2CO_3 by sintering the metal-carbonate compact at a temperature higher than the melting point of K_2CO_3 (891°C). K_2CO_3 decomposes to K_2O and CO_2 and the resultant CO_2 pushes the liquid K_2O and K_2CO_3 out of the compact, leaving behind a porous steel specimen largely free of K_2CO_3. In the dissolution route, the metal-carbonate perform is sintered at a temperature lower than 891°C and K_2CO_3 is subsequently dissolved by hot water. This paper compares the effects of the two routes of LCS on the mechanical properties of porous steel.

Experimental

The LCS process was used to produce the porous steel specimens [3, 4]. Astaloy A steel powder with a particle size <100μm was mixed with K_2CO_3 granules at a specific volume ratio. The volume percentage of steel in the mixture was from 25% to 40%. The mixture was compressed in a steel tube by a hydraulic press at 200MPa, and was sealed by a 10mm thick iron layer using pure iron powder. The compact was sintered in a conventional furnace and then air cooled to the room temperature.

Both routes of LCS, decomposition and dissolution, were used to produce porous steel specimens. In the dissolution route, the compacts were sintered at 850°C for 4 hours. Subsequently the K_2CO_3 in the sintered compacts was dissolved by hot water. In the decomposition route, the compacts were sintered at 1000°C for half hour.

Another set of specimens were produced by combining dissolution and re-sintering. The compacts were first sintered at 850°C for 4 hours and the K_2CO_3 was removed by dissolution in hot water. The specimens were then further sintered at 1000°C for half hour.

The effects of porosity, pore size and compaction pressure on the mechanical properties of the specimens produced by these three routes were studied. The porosities studied were 75%, 70%, 65% and 60%, corresponding to the relative densities of 0.25, 0.30, 0.35 and 0.40. The pore size ranges were 250-425μm, 425-710μm, 710-1000μm and 1-1.5 mm. The compaction pressures were 100, 150, 200, 250 and 300MPa. Except for the parameter being varied, the other parameters were maintained at the standard condition: pore size: 250-425μm, relative density: 0.30 and compaction pressure: 200MPa. The porous steel specimens were machined to cuboids of 45mm×10mm×10mm for three-point bending tests and to cylinders 10mm in diameter and 20mm in thickness for compression tests.

In a three-point bending test, the flexural strength σ and the flexural modulus of elasticity E (termed elastic modulus thereafter in this paper) were calculated from the load-deflection curve by:

$$\sigma = \frac{3FL}{2bd^2} \quad E = \frac{mL^3}{4bd^3} \tag{1}$$

where F is the maximum load, L is the span of specimen between the two supports (45mm), b is the width (≈10mm), d is the thickness (≈10mm) and m is the slope of the initial linear portion of the load-deflection curve. In a compression test, the compressive strength was the maximum stress on the stress-strain curve and the apparent modulus was the slope of the initial linear portion of the stress-strain curve.

Results and Discussion

The flexural strength, compressive strength and modulus of the porous steel specimens manufactured by decomposition and dissolution as a function of relative density are shown in Figure 1. They all increase with increasing relative density. At a low relative density of 0.21, the compressive strength, flexural strength, elastic modulus obtained in three-point bending and apparent modulus obtained in compression of the specimens produced by the decomposition and dissolution routes are similar. When the relative density is increased to above 0.21, there are significant differences between the two methods. The properties of the specimens produced by the decomposition route are significantly higher than those produced by the dissolution route. The differences increase with increasing relative density. At a low relative density of 0.37, the compressive strength, flexural strength, elastic modulus and apparent modulus of the specimens produced by the decomposition route are nearly 116%, 102%, 248% and 183%, respectively, higher than those of the specimens produced by the decomposition route.

These results show that the porous steel specimens produced by the decomposition route were generally much stronger and stiffer than those produced by the dissolution route. This is mainly because the decomposition route used a higher sintering temperature, which resulted in better bonding between the steel particles.

Figure 2 shows the effects of pore size on the flexural strength and apparent modulus of the specimens produced by the decomposition and dissolution routes. For the same porosity, bigger pores resulted in higher flexural strength and apparent modulus. This is mainly because bigger pores result in thicker necks between the steel particles and thus a stronger structure. It is shown again that the porous steel specimens produced by the decomposition route were generally stronger and stiffer than those produced by the dissolution route. The differences increased with increasing pore size.

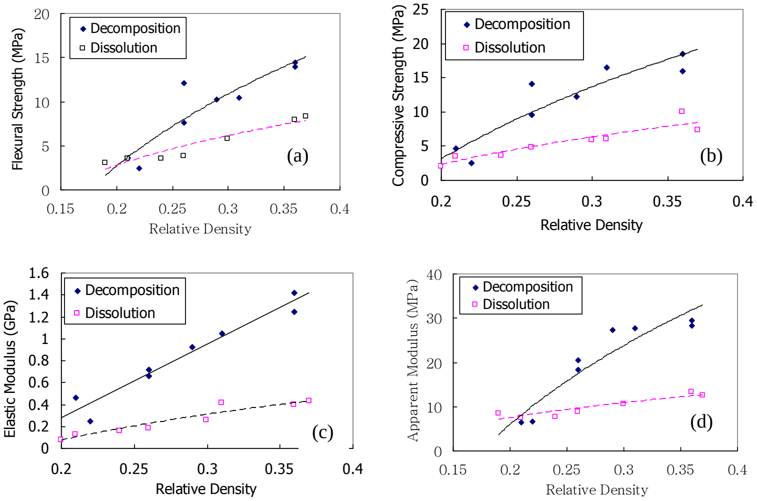

Figure 1. Effects of relative density on (a) flexural strength, (b) compressive strength, (c) elastic modulus and (d) apparent modulus of porous steel produced by the decomposition and dissolution routes. Pore size: 250-425 mm. Compaction pressure: 200 MPa.

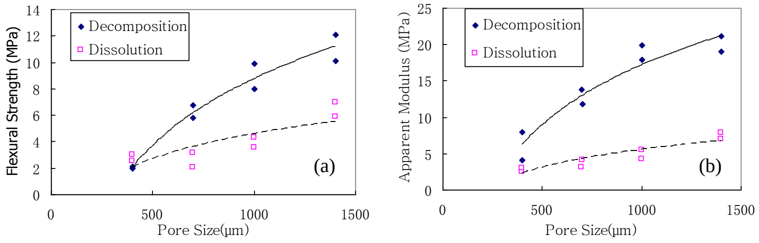

Figure 2. Effects of pore size on (a) flexural strength and (b) apparent modulus of porous steel produced by the decomposition and dissolution routes. Relative density: 0.3. Compaction pressure: 200 MPa.

Figure 3 shows the effects of compression pressure on the flexural strength and apparent modulus of the specimens produced by the decomposition and dissolution route. Higher compaction pressures resulted in higher flexural strength and apparent modulus, because higher pressures resulted in better contacts between the steel particles, which in turn resulted in better bonding after sintering and thus higher strength. At all compaction pressures, the flexural strength and apparent modulus of the specimens by the decomposition route were approximately 83% and 150% higher than those of the specimens produced by the dissolution route.

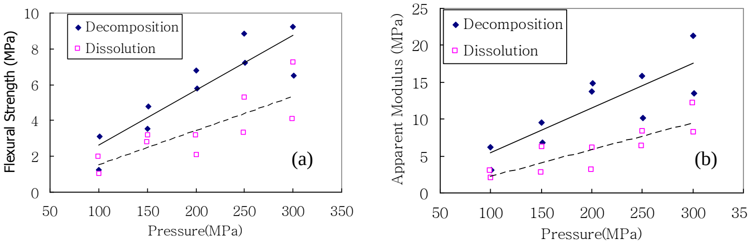

Figure 3. Effects of compaction pressure on (a) flexural strength and (b) apparent modulus of porous steel produced by the decomposition and dissolution routes. Relative density: 0.3. Pore size: 250-425 μm.

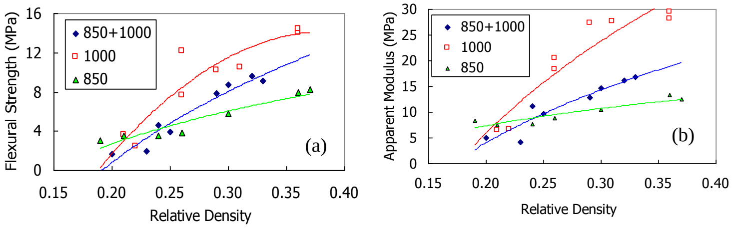

Figure 4. Comparison of (a) flexural strength and (b) compressive strength between the decomposition, dissolution and re-sintering routes. Pore size: 250-425 μm. Compaction pressure: 200 MPa.

Figure 4 compares the flexural strength and apparent modulus values of the specimens produced by the three different routes: decomposition, dissolution and re-sintering. Because the re-sintering route involved two sintering stages, i.e., 850 ℃ for 4 hours and 1000 ℃ for half hour, the specimens produced by this route would be expected to be stronger than those produced either by decomposition or by dissolution alone. In fact, they were always weaker than those produced by decomposition. At low relative densities, they were even weaker than those produced by dissolution alone. They only became stronger than those produced by dissolution at higher relative densities. This anomaly is very likely due to the difference in cleanliness of the specimens between the decomposition and dissolution routes. Because of the small pores, it is difficult to dissolve the K_2CO_3 completely in water. During re-sintering, the residual K_2CO_3 decomposes into K_2O and CO_2. Because the limited amount of CO_2 generated can escape easily without the "pushing" effect, molten K_2O dwells in the specimens and attacks the steel structure, leading to weaker cell walls. This problem is especially serious for specimens with low relative densities, when the steel struts are thinner. The corrosion damage may outweigh the strengthening effect of further sintering. Overall, the one-step decomposition route is the best option in terms of maximising strength and stiffness of the porous steel.

Conclusion

The flexural strength, compressive strength and elastic modulus of the porous steel specimens produced either by the decomposition route or by the dissolution route increased with increasing relative density, pore size and compaction pressure. The specimens produced by the decomposition route were generally much stronger and stiffer than those produced by the dissolution route when the relative density was above 0.21, because the higher sintering temperature in the decomposition route resulted in better bonding between the steel particles and thus stronger cell walls. The specimens produced by combining dissolution and re-sintering were weaker than those produced by decomposition alone. This was likely because residual K_2CO_3 left in the specimens after dissolution could decompose to form molten K_2O during the subsequent re-sintering, which attacked and weakened the steel structure.

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