Innovative Approach to Sintering Aluminum and Aluminum Alloy Powders for Rapid Manufacturing Applications

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Abstract

A new approach to sintering loose packed, coarse aluminum alloy powder to full or near full density is presented. A controlled amount of water vapor is introduced into the sintering atmosphere, which disrupts the oxide film and allows metallurgical contact between particles. In addition, supersolidus liquid phase sintering is used to sinter the part to full density. Since the method is particularly applicable to uncompacted powders, it is potentially useful for sintering aluminum powder preforms manufactured by 3DPrinting and powder injection molding.

Keywords : aluminum, sintering, rapid manufacturing

1. Introduction

The oxide film inherent on aluminum powders is a barrier to sintering, preventing strong bonds between powder particles; therefore, to sinter aluminum powder the alumina film has to be at least partially ruptured. In non-compaction fabrication processes, such as the rapid manufacturing technology of 3DPrinting, reaction methods, as opposed to mechanical mechnisms, must be used to rupture the oxide film.

Previous study has shown that water vapor, contrary to conventional wisdom, has a beneficial effect in disrupting the alumina film on powder particles. Active crystalline gamma-alumina presents an unusual surface chemistry, behaving as a “reactive sponge” by storing and releasing moisture.[1] The optimum temperature for this reaction was found to be approximately 600°C.[2]

To reach full density from an initial density less than 60%, sintering in the presence of liquid is necessary. For example, Schaffer *et al.*[3] found that alloy powder mixed with tin and magnesium can be gravity sintered to near full density because tin melts at the sintering temperature. Though liquid tin does not wet alumina very well at the sintering temperature,[4] the addition of magnesium breaks up the dense oxide film, changes the wetting characteristics, and facilitates sintering.[5] Such additions, however, increase the already high potential for explosion of aluminum powders. Rather, liquid phase sintering of aluminum alloy powders must be used through careful control of the sintering temperature.

This research work presents a method to sinter coarse aluminum alloy powder (+325mesh), having an initial density less than 60% of theoretical density, to full density components without using sintering aids. The method includes controlled use of water vapor in the sintering atmosphere, and heating to temperatures between the solidus and the liquidus using supersolidus liquid phase sintering (SLPS).

2. Experimental and Results

To determine the effect of water vapor additions, a commercially pure aluminum powder, grade UN No. 1396, average particle size in the range of 17 to 30 microns, was used. The powder was poured into a cylindrical alumina crucible and tapped lightly, giving a density of approximately 60%, similar to that of material fabficated by 3DPrinting. Each sample was heated in a tube furnace with a nitrogen atmosphere containing a preselected partial pressure of water vapor. Results of density measurements of the samples are given below.

Table 1. Sintered densities of a commercially pure aluminum powder

Sintering Temperature	Water vapor pressure	Relative sintered density
630°C	0	No sintering
630°C	0.014kPa	74.4%
635°C	0.004kPa	83.3%
635°C	0.009kPa	80.8%
635°C	0.018kPa	74.9%
640°C	0.004kPa	75.3%
640°C	0.017kPa	No sintering

A controlled amount of water vapor in the sintering atmosphere can have a beneficial effect on sintering of pure aluminum powders, and an optimum combination of sintering temperature and moisture content is apparent.

To determine the effectivenessof SLPS and moisture content, atomized aluminum alloy powder UN No. 6061 was used (0.6 Si, 0.07 Cr, 0.25 Cu, 0.25 Fe, 0.89 Mg, 0.03 Mn, bal. Al). The powder was screened to −140 /+325 mesh (< 109 microns/ > 45 microns).

Magnesium and silicon are primary alloying elements in 6××× series aluminum alloy, and Al-Si forms a low temperature eutectic at 577°C, providing the basis for SLPS. For example, the aluminum alloy 6061 has solidus temperature of 582°C and liquidus temperature of 652°C, so heating between these limits would enable SLPS of aluminum alloy 6061.6

Aluminum alloy 6061 powder was processed exactly the same as alloy 1396. Table 3 gives the resulting sintered densities.

Table 3. Sintered densities of prealloyed 6061 powder

Sintering Temperature	Water vapor pressure	Relative sintered density
630°C	0	No sintering
630°C	0.014kPa	64.3%
635°C	0.004kPa	85.4%
635°C	0.009kPa	99.1%
635°C	0.018kPa	78.6%
640°C	0.004kPa	84.2%
640°C	0.017kPa	No sintering

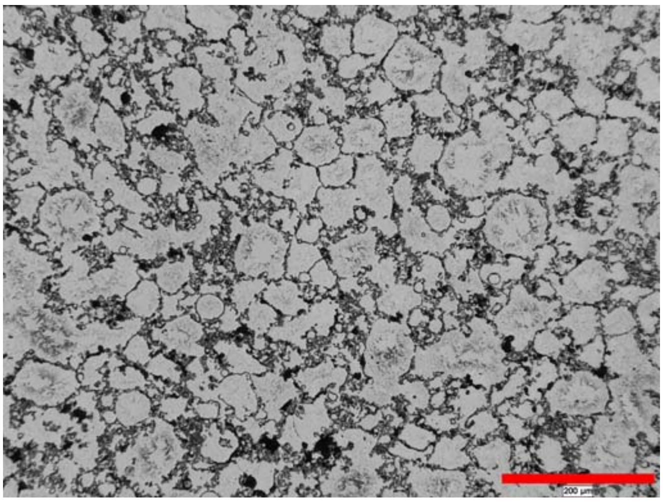

Fig. 1. Microstructure of the sample sintered at 635°C in a nitrogen atmosphere having 0.009 kPa partial pressure of water vapor. Relative density is 99.1%.

Within the limited range of parameters tested, nearly full density was obtained at 635°C with a water vapor partial pressure of 0.009kPa. Densification of coarse prealloyed particles giving full-density products is possible *via* SLPS. Liquid formation at the particle contacts, at the grain boundaries, and within the particles, leads to rapid densification. Formation and spreading of liquid enhance disruption of oxide.

3. Summary

While only a few embodiments of the present work have been shown, it can be concluded that the metallurgical bonds between aluminum particles are created with the help of limited moisture. A possible mechanism of the bonding is that alumina film in the contacts between aluminum particles migrate outward and bring two particles together, instead of breaking or reduction of the aluminum film. Once the metallurgical bonds between aluminum alloy particles are created, sintering at the temperature between solidus and liquidus can consolidate the porous parts to near full density.

4. References

1. K. Sohlberg, S. J. Pennycook, and S. T. Pantelides, “Hydrogen and the structure of the transition aluminas”, *J. Am. Chem. Soc.*, 1999, vol. 121, p. 7493-7499.
2. J. F. Flumerfelt and I. E. Anderson, “The Surface Chemistry of Pure Aluminum Powders as Measured with Quadrupole Mass Spectrometry”, *Advances in Powder Metallurgy & Particulate Materials-1998*, 1998, vol. 2, Metal Powder Industries Federation, Princeton, NJ, pp. 9-39.
3. G. B. Schaffer, T. B. Sercombe, R. N. Lumley, and, S. H. Huo, “On the Design of Sintered Aluminum Alloys”, Proceedings of the First International Conference on Powder Metallurgy Aluminum &Light Alloys for Automotive Applications, MPIF, November 10-11, 1998, Dearborn, MI, pp. 43-50.
4. L. G. Li, D. Chatain, L. Coudurier, and N. Eustathopoulos, *J. Mater. Sci. Lett.*, 1988, vol. 7, pp.961-63.
5. R.N. Lumley, T.B. Sercombe, and G.B. Schaffer, “Surface Oxide and the Role of Magnesium during the Sintering of Aluminum”, *Matall. Mater. Trans. A*, 1999, vol. 30A, pp. 457-64.
6. ASM Metal Handbook, *Properties and Selection: Nonferrous Alloys and Special Purpose Materials*, vol. 2, ASM International, OH, 1990.