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Characterization of the microstructure, mechanical properties, and shot peening response of an industrially processed Al–Zn–Mg–Cu PM alloy

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ABSTRACT

The objective of this study was to characterize the mechanical/physical properties of an industrially processed Al–Zn–Mg–Cu powder metallurgy (PM) alloy and assess the subsequent effects of shot peening. The research involved a number of experimental techniques, including density measurements, tensile testing, Rockwell hardness measurements, nano-indentation, and optical and scanning electron microscopy. Residual stress measurements were completed using a combination of X-ray diffraction (XRD) and neutron diffraction (ND). Industrially produced specimens attained near full theoretical density and exhibited a nominal yield strength on the order of 460 MPa in the T6 condition. It was discovered that zinc had preferentially evaporated from the surface of the components during sintering. The depleted region persisted to a depth of ≈3 mm and resulted in reduced nano-hardness of 1.65 GPa at the surface versus 2.50 GPa in the bulk. Shot peening increased the surface hardness of the alloy and resulted in a peak compressive residual stress of 232 MPa at the treated surface.

1. Introduction

As the automotive industry continuously strives to reduce vehicle emissions there is an increasing desire for high performance, lightweight materials that can be produced in an economical manner. One option that has become progressively more attractive is that of aluminum powder metallurgy (PM). The commercial inception of this technology began in the mid 1990s with the introduction of aluminum PM camshaft bearing caps. In recent years, significant effort has been put into developing aluminum PM materials that can be used to expand the scope of automotive applications. With 7xxx series wrought aluminum systems having some of the highest mechanical properties among all aluminum alloys, it is not surprising that alloys with similar chemistries have been devised for PM processing. One such alloy that has now matured into a commercial product is referred to as Alumix 431D. This blend was developed for press-and-sinter processing by Ecka Granules and was seemingly designed on the basis of the wrought alloy AA7075.

The open literature on this alloy is exclusively focused on laboratory processing, and more specifically, the development of optimized sintering schedules. Various studies have found that the blend responds very well to traditional press-and-sinter processing with both Martin and Castro (2003) as well as Azadbeh and Razzaghi, 2009 achieving sintered densities >98% with proper sinter temperature and time, while Pieczonka et al. (2012) compared the effects of various sintering atmospheres, finding that nitrogen produced a superior sinter quality when compared to both argon and a nitrogen–hydrogen mixture. Additional studies have shown the heat treatment response to be similar to that of wrought AA7075, with LaDelpha et al. (2009) finding the yield strength of the PM system in the T6 state to be approximately 91% that of the wrought system.

While there has been a considerable amount of sintering-based research dedicated to Alumix 431D, minimal data exists on its response to critical secondary operations such as shot peening. Shot peening has been extensively used in industry for years to improve the fatigue performance of wrought aluminum alloys with numerous studies published to ascertain the effects of shot peening on wrought AA7075 with varying results. Both Benedetti et al. (2009) and Wagner et al. (2011) saw gains in fatigue strength of approximately 50% with select peening parameters. However,

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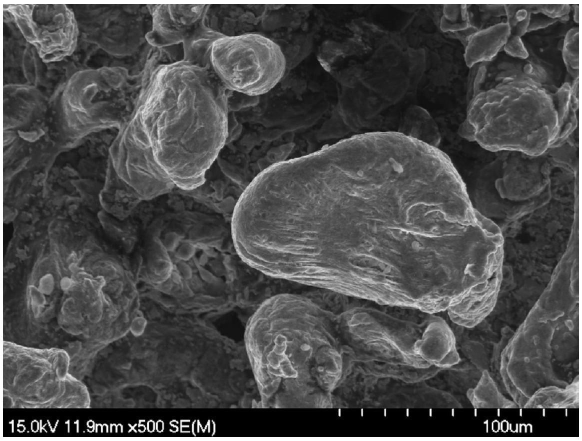

Fig. 1. SEM image of PM7075 raw powder.

others including Honda et al. (2005) and Grendahl et al. (2007) saw little to no improvements in the fatigue strength of AA7075 by peening, while Oguri (2011) saw no gains from conventional shot peening, but slight improvements with a fine particle shot peening process. Although there have been varying results describing the effectiveness of shot peening as a means to extend the fatigue life of AA7075, it is clear that with proper peening parameters, appreciable gains can be realized by shot peening aluminum alloys.

Overall, it is clear that Alumix 431D is a promising PM material. However, an acute lack of data in the areas of industrial processing behavior and value-added secondary operations remain as impediments to widespread exploitation. Hence, the objective of this research was to simultaneously address both shortfalls by producing samples of the alloy in a high volume industrial production cell and then conducting a detailed metallurgical assessment of sintered specimens both before and after a conventional shot peening operation.

2. Materials

The material of interest in this study was the commercial Al–Zn–Mg–Cu system referred to as Alumix 431D. The blend was produced by ECKA Granules (Fürth, Germany) through air atomization and is generically denoted as PM7075 throughout the study. An SEM image of the raw powder can be seen in Fig. 1, showing the irregular morphology typical of air atomized materials. This particular powder blend was designed for direct press and sinter processing and was formulated from a mixture of a master alloy powder containing aluminum and all alloying additions, pure aluminum powder, as well as a powdered lubricant (Licowax C; Clariant Corporation) added to aid die compaction. The targeted and measured compositions of the PM system, found by atomic absorption, can be seen in Table 1.

3. Experimental techniques

The samples for study were prepared industrially using a conventional die compaction and sintering approach. Initially, green compacts were produced through double action die compaction under an applied pressure of 400 MPa. All compacts were plate-shaped with nominal dimensions of 100 mm × 75 mm × 17 mm. The green compacts were then sintered in a continuous mesh belt furnace under a high purity nitrogen atmosphere. The nominal thermal cycle consisted of a 20 min dwell at 400 °C for de-lubrication, followed by sintering at 605 ± 5 °C for 20 min and gas quenching to ambient temperature in a water jacketed section of the furnace. During the sintering process the atmospheric oxygen content was held <10 ppm while the dew point was <−60 °C. All sintered plates were then heat treated to the T6 condition. This process included solutionization at 470 °C for 90 min followed by water quenching and artificial aging at 125 °C for 24 h. Both thermal stages of heat treatment were conducted in air.

To study the effects of shot peening on the T6 material, the pucks were sectioned to a size appropriate for the automated peening system (approximately 50 mm × 50 mm) and the surface was peened to an Almen intensity of 0.4 mm N. Harding et al. (2010) found this intensity to produce noticeable plastic deformation in the treated surface while minimizing excessive damage to the material. The tolerance on the intensity was +0.02 mm N, −0.00 mm N (+5%, −0%) and was verified using standard N-S Almen strips before and after peening of the PM plates according to SAE J442 (1995). To minimize surface contamination of peened specimens, zirconium oxide shot was utilized as the peening media (with a diameter of 300 μm). This resulted in uniform deformation of the treated material without any obvious material transfer or damage to the shot.

Characterization of the pucks began with measurements of sintered density, apparent hardness and tensile properties. The sintered density of the samples was measured by a standard Archimedes approach coupled with oil infiltration. Hardness measurements were completed with Rockwell and nano-indentation systems. Rockwell data were gathered from the surface of T6 pucks in the HRB scale using a Leco R600 Rockwell Hardness Tester. Nano-indentation was employed to assess sub-surface hardness gradients using an Agilent G200 system equipped with a continuous stiffness measurement module. Indentations penetrated to a depth of 1000 nm with the hardness being determined from an indentation depth of 400 to 900 nm. To determine the tensile properties of T6 specimens, heat treated pucks were sectioned and machined into threaded-end round tensile bars per ASTM E8-M (2007). Tensile testing was completed using an Instron 5594-200HVL hydraulic frame equipped with a 50 kN load cell. All specimens were loaded at a rate of 5 MPa/s with strain data collected using an Epsilon model 3542 axial extensometer that remained attached to the specimen through fracture. As such, the reported values for elongation represent the sum of elastic and plastic strain components.

The next means of characterization emphasized microstructure assessment. Here, optical and electron microscopy were employed together with X-ray diffraction (XRD) and optical profilometry. To characterize the surface condition of both the heat treated and peened materials a combination of scanning electron microscopy (SEM) and non-contact optical profilometry was utilized. Surface imaging was completed using a Hitachi S-4700 cold field emission SEM operated at an accelerating voltage of 15 kV and beam current of 10 μA. Surface topography was studied using a Nanovea Micro-Profiler, model PS50, equipped with a 1.2 mm sensor. Data acquisition was completed using Nanovea 3D software with Nanovea Mountains Pro 3D used for analysis including surface roughness measurements. For subsurface analysis, samples were sectioned perpendicular to the free sintered surface and mounted in epoxy. Mounts were then ground and polished through standard metallographic procedures. The microstructure was analyzed optically using an Olympus model BX51 optical microscope. In addition, chemical analyses were completed using a JOEL JXA-8200WD/ED electron-probe micro-analyzer (EPMA) operated at an accelerating

Table 1
Targeted and measured chemistries of PM7075 (wt%).

	Al	Cu	Mg	Zn	Sn
Target	Balance	1.6	2.5	5.5	0.2
Measured	Balance	1.60	2.62	5.59	0.14