Novel Aluminum-Carbon Materials

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ABSTRACT

We characterize novel metal carbon materials called covetics. More specifically we study a warm-rolled aluminum alloy (Al 7075) with up to 5 wt% of carbon infused during processing. At the macroscale, we measured mechanical properties: Young's modulus, ultimate tensile strength (UTS), 0.2% yield strength (YS), and tensile elongation at failure. At the mesoscale, we measured Rockwell and Vickers hardness, and, at the microscale, we measured local elastic modulus and hardness using a nanoindentation technique. In parallel, we characterized the microstructure of these materials at different structural scales using scanning electron microscopy (SEM) and transmision electron microscopy (TEM). The following enhancements in properties over the corresponding base materials were observed: 1. higher strength (UTS, YS) 2. higher hardness (Rockwell, Vickers and nanoindentation) 3. larger elongation, and 4. lower density, as carbon content increased. In summary, the results show that Al 7075 covetics exhibit superior mechanical properties to the corresponding base metals, which makes them very good candidates for range of engineering applications.

Keywords: nanocarbon, covetic, nanomaterial, metal-matrix composite

1 BACKGROUND

Covetics are a new class of materials which were recently invented by Third Millennium Metals (TM^2), LLC (Waverly, Ohio). Covetics are metal-carbon materials which consist of a metal matrix (made of copper, aluminum, zinc, silver, gold or other base elements) and carbon combined with metal in a new, yet unknown way [1]. TM^2 has filed composition of matter patents for several base elements that are currently patent pending and developed a new processing method (patent pending) that allows infusion into these metals significant amounts (up to 15 wt% to date) of carbon. In this paper 7075 aluminum alloy covetics are studied. This study extends earlier studies on covetics [2-5].

2 MATERIALS

We characterize the composition, structure, and mechanical properties of aluminum covetics, 7075 Al, with 0, 3 and 5 wt% carbon (C), which were supplied by TM^2. In figures, we denote these three types of materials as 7075_0NC, 7075_3NC, and 7075_5NC, respectively. The weight percentages of carbon are the processing compositions as reported by TM^2. The materials were in the T0 condition and warm-rolled five times to a thickness of 1.0 mm (0.04 in) from the as-cast 1.0 cm (0.40 in) thick sheets. All three billets were cast in the same durance and rolled in the same batch after side by side homogenization. The characterization techniques included density measurement, structure imaging using scanning electron microscopy (SEM), transmission electron microscopy (TEM), composition measurements using SEM- and TEM-energy dispersive spectroscopy (SEM-EDS and TEM EDS), and mechanical testing including tensile, hardness, and nanoindentation tests.

3 DENSITY

Densities were obtained experimentally by measuring the weights and volumes of at least five samples of 50 × 25 × 1 mm^3 sizes. The edges and sides were polished to have smooth and parallel edges prior to measurements. Sample dimensions were taken at three different locations and the values were averaged. Theoretical densities for the samples were also predicted by applying a rule of mixtures as shown in equation 1.

$$\text{Theoretical density} = \rho_f v_f + \rho_m v_m \quad (1)$$

where ρ_f is a filler density, ρ_m is a matrix density, v_f is a volume fraction of filler, and v_m is a volume fraction of matrix.

Table 1. Measured and theoretically obtained densities of 7075 Al covetics (units: g/cc).

Material	Carbon weight %	Measured Density	Theoretical Density
7075_0NC	0	2.79 ± 0.22	2.81
7075_3NC	3	2.77 ± 0.19	2.78 - 2.79
7075_5NC	5	2.76 ± 0.20	2.76 - 2.77

In calculations we assumed the density of amorphous carbon as 1.8-2.1 g/cm^3 and the density of 7075 Al as 2.81 g/cm^3 and no voids. Measured densities, which agreed with theoretical predictions (Table 1), were slightly lower for covetics. Measured densities were 2.79, 2.77 and 2.76 g/cc for three carbon levels, respectively. Such small variation in density can be attributed to a low volume percentage of the infused carbon and the fact that carbon has density which is fairly similar to that of the elemental aluminum. Theoretical densities were predicted by using the rule of mixtures as summarized above. In calculations we assumed the density of an amorphous carbon as 1.8-2.1 g/cc and the density of 7075 Al as 2.81 g/cc and no voids. Measured densities were almost identical to theoretical ones; see Table I.

4 TENSILE TEST RESULTS

Tensile specimens were prepared in accordance with ASTM Standard E-8/E8M-09 sub-size specifications with a

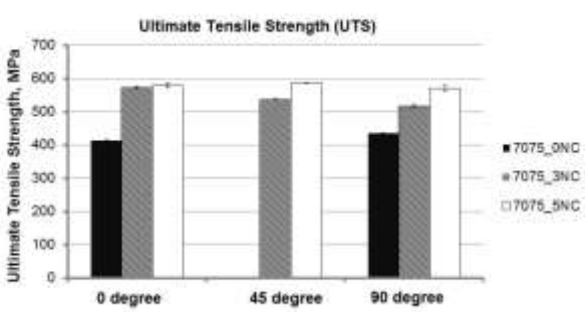

Fig. 1. Ultimate tensile strength

25 mm (1.0 in) gauge length. The tensile test was performed in air at room temperature using an MTS servo hydraulic materials testing machine (MTS 22 kips load cell) operated at a constant crosshead speed of 0.0254 mm/s (0.001in/s). Four samples of each kind were machined to the same length in three different orientations (0^0, 45^0, 90^0) to the direction of rolling, without changing the dimensions for tensile test. Load-displacement data were recorded and used to obtain stress-strain curves and calculate Young's modulus E, ultimate tensile strength UTS, 0.2% yield strength YS and % elongation %EL. The results show considerable increase in UTS and 0.2% YS for covetics as compared to the base Al alloy (Figs. 1 and 2). The UTS

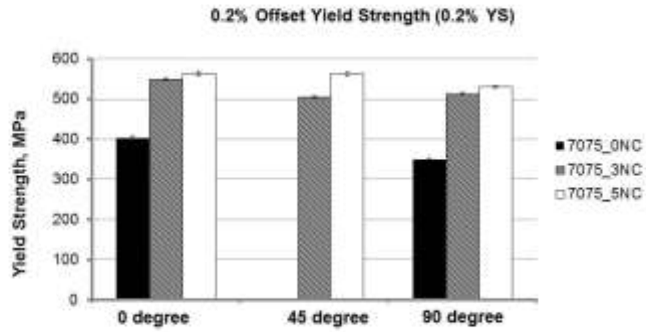

Fig. 2 0.2% yield strength.

increased by 40% (from 0 to 5% C) for a 0 degree orientation, from about 400 MPa to nearly 600 MPa. Similarly, 0.2% YS increased by 41% (from 0 to 5% C) for covetics as compared to base Al alloy at 0^0 orientation. Note that strength increased significantly higher than the strain hardening created by the rolling process alone. From Al data from the Aluminum Association's Engineering Data for Aluminum Structures, standard Al 7075-0 as cast has a UTS = 275 MPa. Ductility also increased for covetics but elastic modulus E remained unchanged.

5 HARDNESS AND NANOINDENTATION

Hardness testing was carried out at different length scales to determine local and global hardnesses of the Al 7075 alloy covetics. The samples were polished using ECOMET 3000 grinder with sand papers having grit sizes 320, 600, 1200 and 2400. Then, the samples were polished using the same polisher with polishing powder (3.0, 1.0, 0.3 and 0.02 micron de-agglomerated alpha alumina) in four stages using polishing cloths. TI 950 TriboIndenter® (Hysitron, Minneapolis, MN, USA) was used to perform nanoindentation tests on the plane parallel to the rolling direction. Indentations were made with a diamond Berkovich tip. Indentation sites were selected using TriboIndenter's optical system. For all test areas, 8000 μN load-controlled indents were done using a five-second load, two-second hold and five-second unload function. Sixteen indentations were conducted on each specimen. Reduced elastic modulus E_r was calculated using equation 2.

$$\frac{1}{E_r} = \frac{(1-\nu_s^2)}{E_s} + \frac{(1-\nu_i^2)}{E_i} \qquad (2)$$

where the subscript i corresponds to the indenter material, the subscript s refers to the indented material, and ν is Poisson's ratio. For a diamond indenter probe, E_i is 1140 GPa and ν_i is 0.07.

Measured quantities were the reduced elastic modulus E_r and hardness H. Both E_r and H increased for covetics (see Figure 4). Reduced Modulus (E_r) and Hardness increased for covetics by 8% and 43% respectively as compared to 7075 Al alloy.

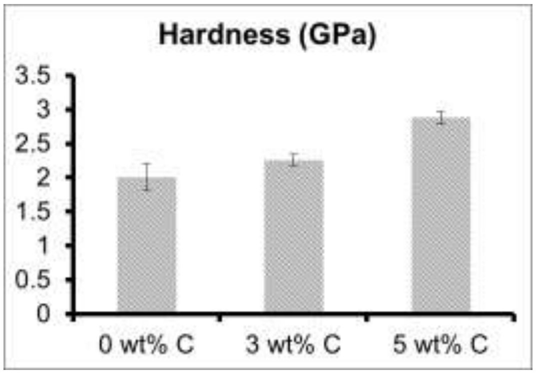

Fig. 3. Hardness measured by nanoindentation.

Vickers micro hardness (VHN) was measured on the surface parallel to the rolling direction by applying a load of 3 kg for 15 sec (Shimadzu microhardness tester HMV-M3, Newage Testing Instruments, Inc., Feasterville, PA, USA). The surface of the specimen was prepared as for the nanoindentation test. The hardness value was the average of five measurements made on the surface of each specimen. Rockwell hardness (HRB) was also measured on the same plane (Wilson/ Rockwell Hardness Tester by Instron, Grove City, PA, USA).

Vickers and Rockwell hardness tests showed improved properties for covetics. More specifically, for 5 wt%C material the Vickers hardness increased by 33%, Rockwell hardness increased by 32% (Figure 1).

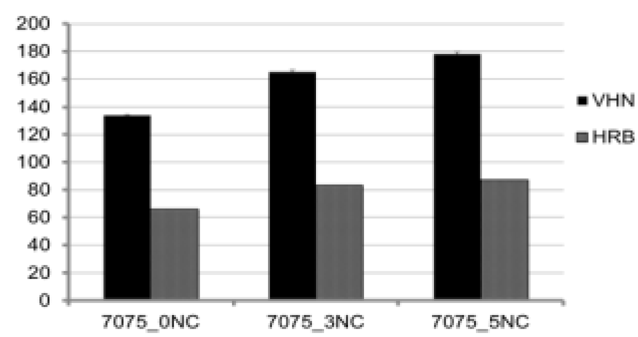

Fig. 4 Vickers (VHN) and Rockwell (HRB) hardness testing.

6 ELECTRON MICROSCOPY

Scanning electron microscopy images were taken by using a Field-Emission Environmental Scanning Electron Microscope (ESEM-FEG) with Energy-Dispersive Spectroscopy (EDS) (Philips XL30 ESEM-FEG, FEI, Hillsboro, Oregon, USA). Tensile fracture surfaces of 7075 Al alloy covetic specimens from zero degree orientation (tested along rolling direction) were imaged. Samples were imaged with no coating or other sample preparation.

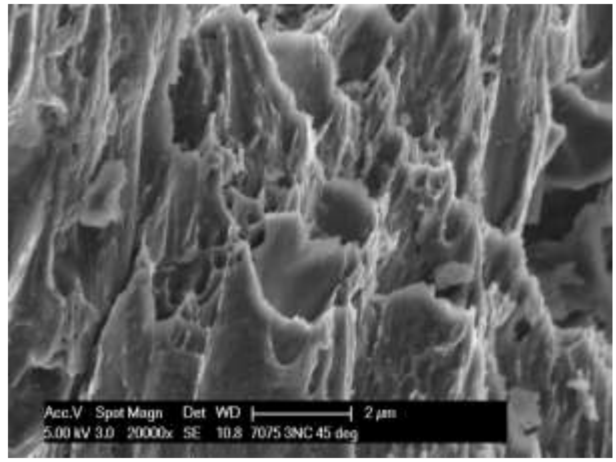

Fig. 5. SEM image of fractured surfaced for 3 wt%C.

Figure 6 shows a bright field image and electron diffraction pattern from an Al 7075 5 %wt C sample. The image shows a

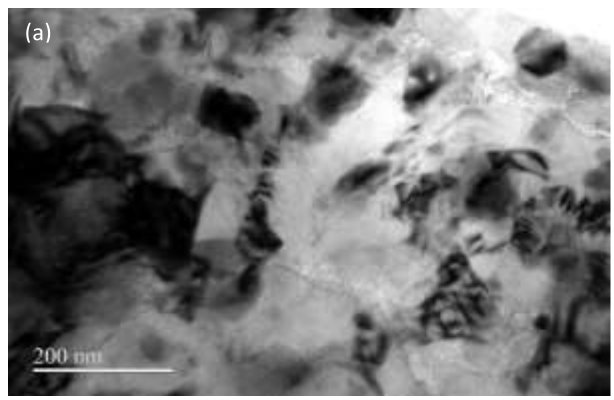

Fig. 6 Bright field image of Al 7075 cv 5% sample ob. Tained by TEM.

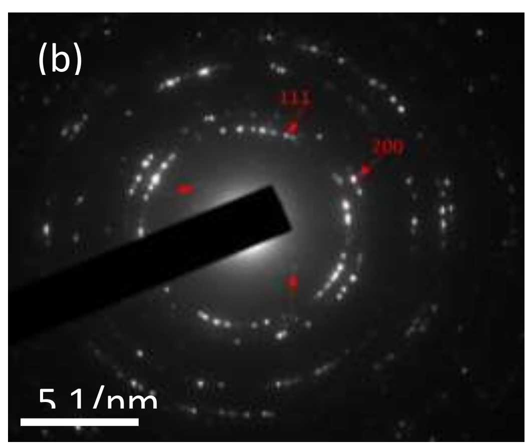

Fig. 6 Bright field image of Al 7075 cv 5% sample obtained by TEM.

polycrystalline region of the sample with a relatively wide range of grain sizes, 50-150 nm, and random orientations of the grains. This observation agrees with the diffraction pattern that shows rings of spots. Some of the spots are stronger indicating that they come from larger grains. The {111} and {200} rings of Al are labeled in Fig. 6. The two spots marked with arrows, and no labels, correspond to an interplanar distance of 0.360 nm. This distance does not agree with any interplanar distance in Al but is close to the (001) C-C interplanar distance in graphite of 0.335 nm. Energy dispersive X-ray data from this sample shown in Fig. 7 shows a C concentration of ~ 3%.

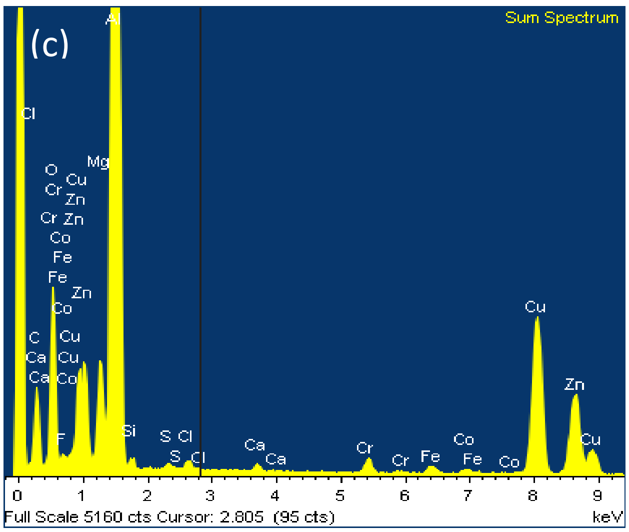

Fig. 7. EDS spectra from the same sample. The EDS shows C concentration of ~3%.

7 CONCLUSIONS

Overall, the warm-rolled 7075 Al covetics showed improved mechanical properties with the increased carbon content. Hardness, measured using Rockwell, Vickers and Nanoindentation testing, increased with an increase in carbon content. Ultimate tensile strength and 0.2% offset yield strength increased significantly while Young's modulus remained unchanged. SEM micrographs illustrated failure characteristics, while TEM images showed a nanoscale grain structure and the EDS data provided qualitative chemical composition of a 3 wt% C sample.

These results show high technological promise of covetics. Further studies are needed to more fully understand these new materials.

8 ACKNOWLEDGEMENTS

Third Millennium Metals, LLC is gratefully acknowledged for supplying covetic materials for this study and for very helpful discussions on this project.

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