Stronger High-Temperature Light Alloys

Enabled by Atom Probe Tomography

Light alloys are used in a myriad of applications from spaceships to golf clubs. They are often developed for cutting-edge applications that require high performance, low mass, and often where the cost is not the overriding factor. The first light alloys developed in the early 1900s were used in the structures of zeppelins and the Wright brothers' first engine – cutting-edge technology at the time. These alloys have a high strength to weight ratio and are used more and more in everyday applications like automobile engine blocks/wheels which enable faster acceleration when you need it as well as better fuel economy overall.

Light alloys are particularly well suited for atom probe tomography (APT) analysis. Nanoscale features are critical to many of these alloys' key performance metrics. APT, unlike most microscopies, has equal sensitivity to all elements including the light elements, specimen preparation is typically straightforward, and the evaporation fields are low relative to their strength, so success rates for APT analysis are high.

The term light metals is traditionally applied to aluminum and magnesium alloys that are frequently used to reduce the weight of structures. Titanium, although substantially denser is included due to its high-strength properties and relatively low mass that results in total weight reduction for most applications. Lithium and beryllium are usually used just as alloying agents as they are dangerous in their pure form. The desire is always to have an alloy that is strong, ductile, corrosion resistant, tolerates high temperatures, etc., but usually, there are tradeoffs. Understanding how the microstructure and localized compositions affect the material properties, i.e. "those tradeoffs," results in the development of better performing light-weight alloys.

In the following analysis completed at Oak Ridge National Laboratory, APT was used to understand mechanisms that prevent coarsening of metastable strengthening phases. This resulted in the development of an AlCu alloy that maintains its strength at higher temperatures than its counterparts allowing for light, strong, and high-temperature cylinder heads for next-generation fuel efficient internal combustion engines. This feat would have been impossible without the 3D nanoscale information APT supplied.

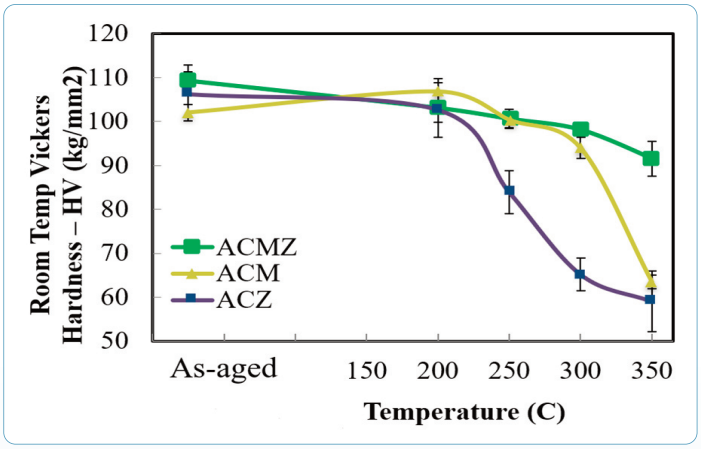


Figure 1:

The newly developed Al-Cu-Mn-Zr (ACMZ) alloy maintains its hardness to conditioning temperatures ≥350 °C, which is a dramatic increase from other AlCu alloys (ACM&ACZ). This alloy was designed for cylinder head applications increasing the operating temperature, and thus fuel efficiency of internal combustion engines. The addition of both Mn and Zr is necessary to stabilize the secondary phases at high temperatures.

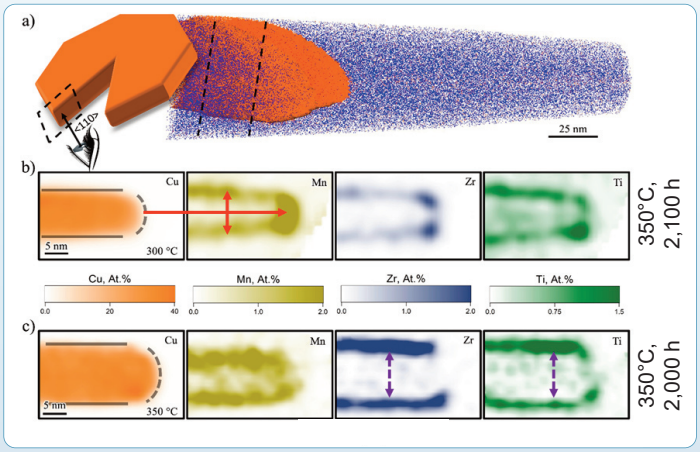


Figure 2:

a) 3D view of a theta-prime precipitate in an AlCu alloy.

b/c) 2D contour plots showing the concentration of Cu, Mn, Zr, and Ti at the precipitate interfaces. The red solid arrows show the segregation of Mn, stabilizing theta-prime interfaces, which gives time for the formation of TiZr rich ordered phases (dotted purple arrows) that keep the phase from coarsening at higher temperatures.

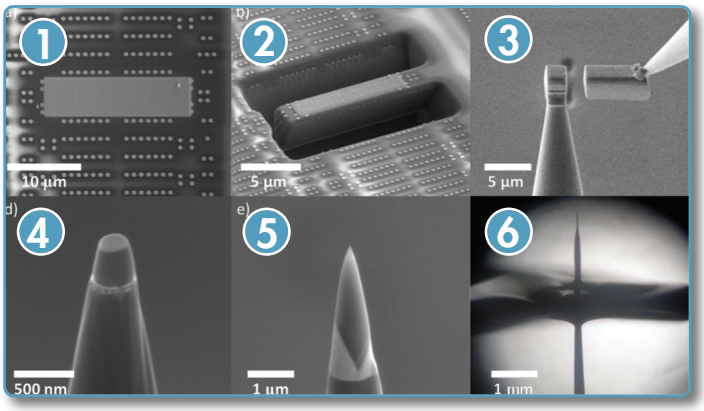
Poplawsky, J. D. et al. Acta Materialia 194, 577–586 (2020)
www.greencarcongress.com/2018/07/20180704-acmz.html

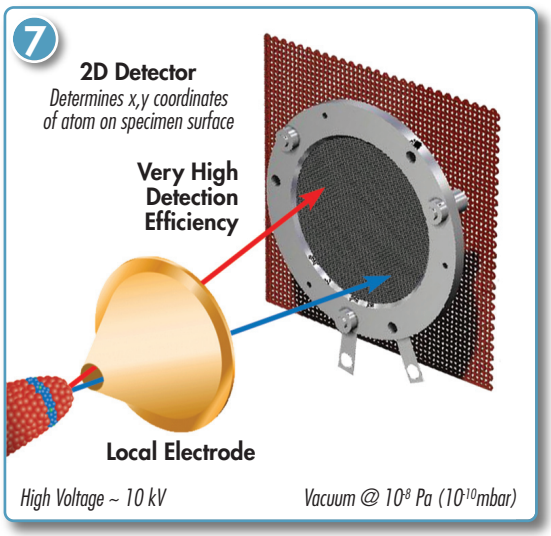
Three Steps to 3D Nanoscale Analysis

An Introduction to Atom Probe Tomography

Step 1: Specimen Preparation

An atom probe specimen usually has a nanoscale region of interest (ROI) requiring both 3D compositional imaging and analysis. The sample is formed into a needle shape containing the ROI. Common APT specimen preparation methods using electropolishing or a Focused Ion Beam system (FIB) are very similar to TEM methods except instead of forming a thin sheet, a needle shaped sample is desired. At the right, standard FIB liftout and mounting of a specimen (figures 1 through 3) and then sharpening the sample with the ROI left at the very apex (4 and 5). In 6, a wire geometry sample is being electropolished.





Step 2: Data Collection

An atom probe produces images by field evaporating atoms from a needle-shaped specimen and projecting the resultant ions onto a detector 7.

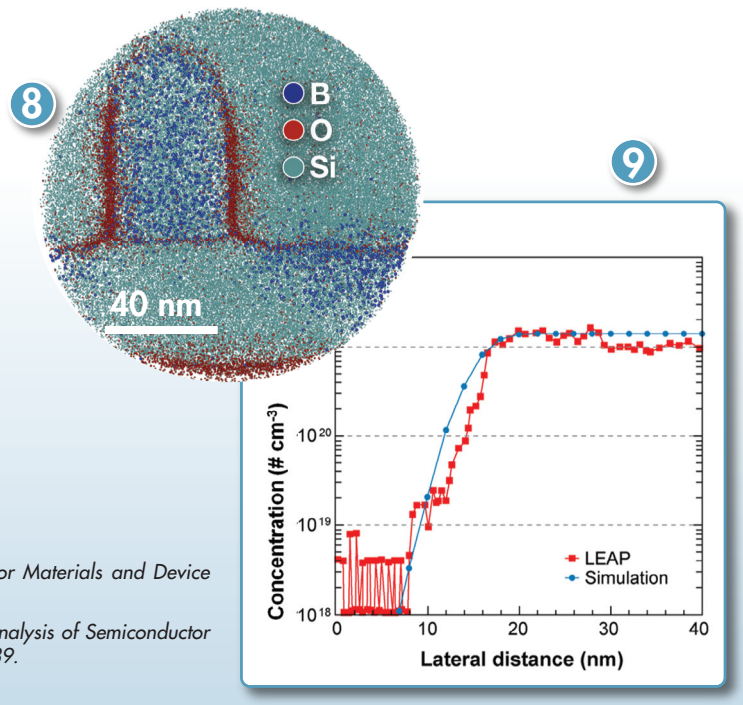
A high magnification results from the ~ 80nm tip being projected onto an 80mm detector resulting in a magnification of approximately 10^6.

An atom probe identifies atoms by their mass-to-charge-state ratio *(m/n)* using time-of-flight mass spectrometry. Charge state, *n*, is typically 1 to 3.

The specimen is held at approximately 50K to reduce surface diffusion during the experiment. The high electric field results in 100% ionization and the high speed detector is capable of measuring up to 80% of the collected ions, independent of ion mass.

Step 3: Data Visualization and Analysis

Examples of data output are illustrated by a slice of a 3D atom map of a transistor† 8, and a dopant composition profile‡ 9. The image shows the positions of individual atoms (oxygen is red and boron is blue) in the transistor with subnanometer resolution. From the reconstructed data set many types of useful analyses are possible. These include 3D visualization, 2D atom mapping 8, 1D depth profiling and line scanning 9, as well as mass spectra and compositional analysis from user-selected volumes.



† *Lauhon, L. J. et al, MRS Bulletin "Atom Probe Tomography of Semiconductor Materials and Device Structures" 34(10) (2009) 738.*

‡ *Moore, J. S.; Jones, K. S.; Kennel, H.; Corcoran, S., Ultramicroscopy "3-D Analysis of Semiconductor Dopant Distributions in a Patterned Structure using LEAP" (2008), 108, 536–539.*

CAMECA® SCIENCE & METROLOGY SOLUTIONS / AMETEK®

www.cameca.com • cameca.info@ametek.com