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TEM – Now We Can Image and Identify Single Atoms; What's Next?

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Henry Sorby first observed alloy structures under a microscope 150 years ago. The TEM appeared 80 years ago (Fig. 1). Now we routinely image and identify individual atoms in materials. The TEM can discern simultaneously, from the micro to the atomic scale, the three factors that control the principal properties of solids: the crystal structure (or lack thereof), the defect structure (or lack thereof) and the atomic chemistry (elemental, bonding). This unique capability evolved, starting in the 1930s and 40s when TEM was just a high-magnification imaging tool. In the 50s and 60s the power of diffraction patterns and their quantitative relationship to the image was realized. In the 70s and 80s various spectrometers were interfaced to the TEM which can quantify the complete range of signals from inelastic beam-specimen interactions. Atomic image resolution was achieved relatively early (mid 70s) and quantification soon followed. However, it took several decades from the first probe-forming TEMs (70s) to the current aberration-corrected, energy-filtering TEMs (Fig. 2) to develop the hardware necessary to produce sub-atomic beams, while retaining the current density to generate detectable and quantifiable signals for atomic-level analysis (Fig. 3). The TEM is unique in that the ~40 different imaging and diffraction signal outputs are all fully quantifiable and can all be simulated in a computer.

This technological progress has brought us to where we can develop new strategic approaches to the TEM of materials:

- Few properties are controlled at the atomic level; most are determined in the 1-100nm range. We can move beyond the TEM's historic focus on resolution and address practical problems (Fig. 4).
- The Materials Genome Initiative focuses on new materials, tailored for specific properties and created in the computer, rather than by the usual "shotgun" alloy approach. Thus we should operate TEMs through computer control rather than relying on traditional approaches (Fig. 5).
- Today's TEM is a data-gathering tool, like the SEM. The future of TEM should be the integration and interpretation of quantitative data from multiple signals. Multi-million dollar TEMs should mainly acquire images that integrate DPs and multi-spectral data at each pixel.
- Multi-element mapping, as in the SEM, means that we can now routinely study complex multi-element engineering materials, rather than focus on more ideal, low-order systems.
- Therefore, "big data", the creation, storage and analysis of tera (and more) bytes should be integrated into the EM community. We should establish open-access data banks of images, DPs and spectra taken on our digital TEMs so no-one has to repeat routine experiments.
- The TEM screen, the crucial interface between the eye/brain and the operator, should use touch and voice-sensitive technology, to enable application of data analytics to all EM data, in real time. Thus, during acquisition, the computer can guide the selection of which specimen area to study such that new information is created, rather than the repetition of previous studies.
- With such an approach, the choice of which areas to study and the effect of specimen preparation on the areas we choose become more, not less, important.
- With the right specimens and the right technology, we should finally address full characterization of the third dimension in our specimens and remove the inherent limitations of 2D projection artifacts from 3D specimens.

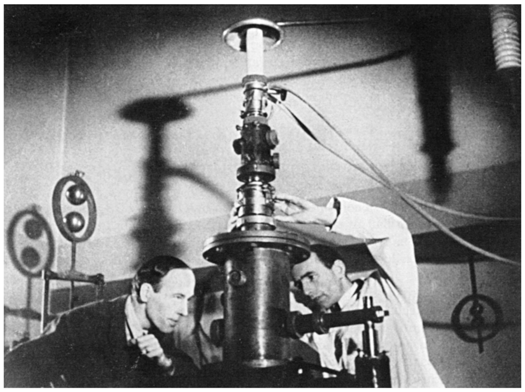

Figure 1. The original Ruska/Knoll TEM

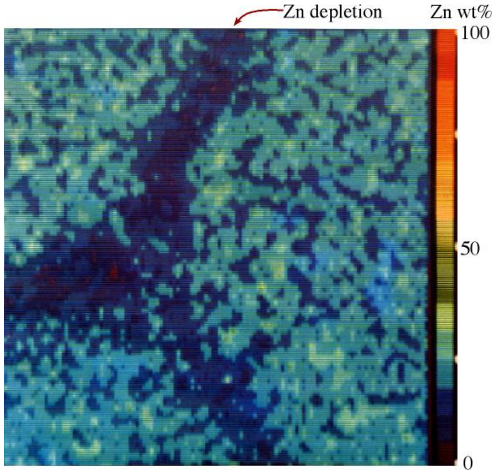

Figure 3a. ~ 1980 digital X-ray map of Zn distribution around a triple point in an aged Al-Zn-Mg alloy (courtesy G.W. Lorimer)

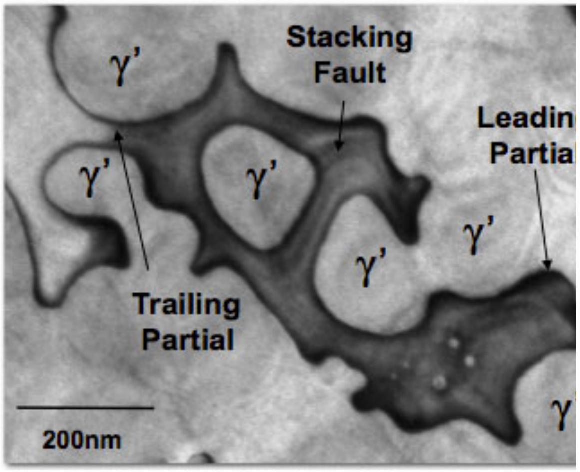

Figure 4. Low magnification STEM BF image showing defect and precipitate contrast in Ni-base superalloy (courtesy M.J. Mills)

Figure 2. Today's TEM, sans operator

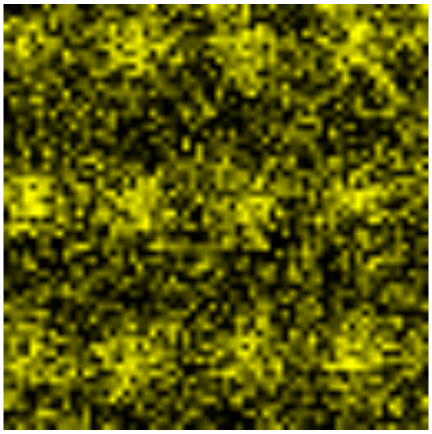

Figure 3b. XEDS map of O columns in $SrTiO_3$ (courtesy D.W. McComb)

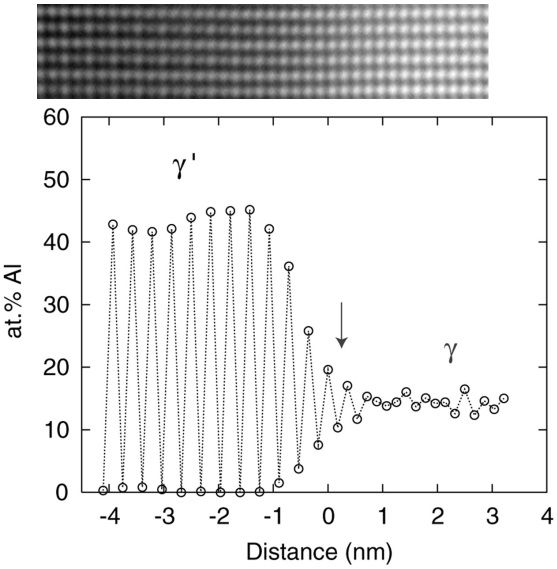

Figure 5 (top HAADF image of Al distribution across Ni-Ni3AL interface: (below) embedded atom model of AL distribution across the same interface (courtesy H.L. Fraser)