ATOMIC SCALE CHARACTERIZATION OF AN AL-STEEL WELD INTERFACE

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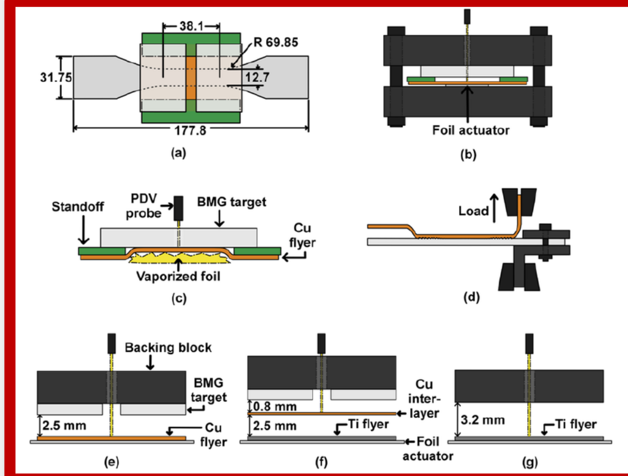
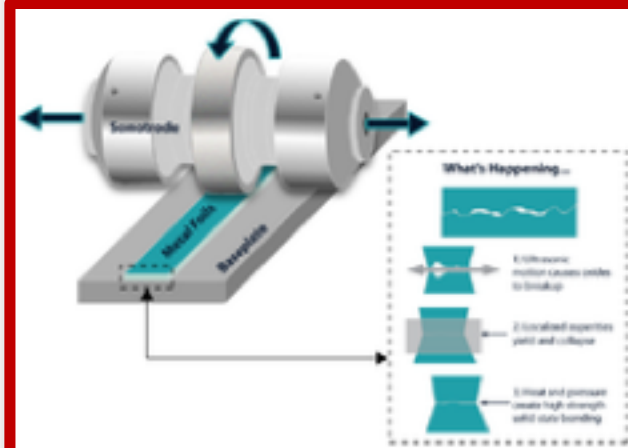
OUTLINE: Answer questions related to oxide dispersion and inter diffusion zone formation at the interface

- **Solid state welding- Introduction**
  - What constitutes solid state welds?
- **Al-Steel solid state welds**
  - State of the art
- **The unanswered questions**
  - Oxide dispersion and IMC formation
- **Interface characterization at an atomic scale**
- **Synergies with other welding processes**
  - Ultrasonic welding and VFAW
- **Unanswered questions and a need for fundamental research**
- **Outlook and future work**





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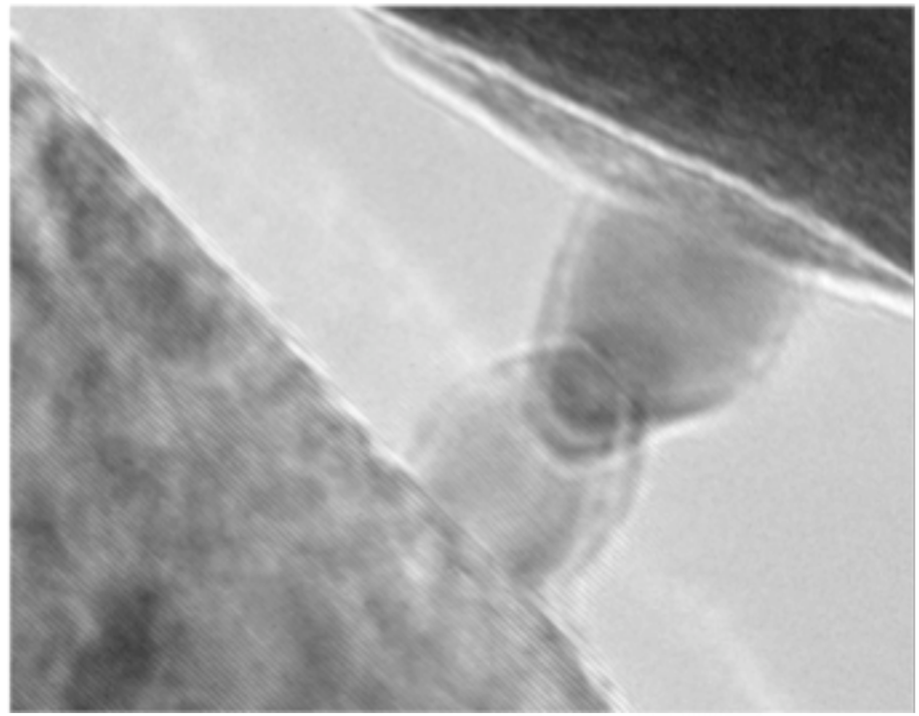
Surface impurities need to be removed to initiate a solid state weld

- Atomically clean metal to metal joining should be spontaneous
- Contact is hindered by three surface barriers:
  - Asperities
  - Oxides
  - Surface contamination
- How do we get rid of these barriers?-
- **Plastic deformation!**
- **More plastic deformation!**
- **Even more plastic deformation!**



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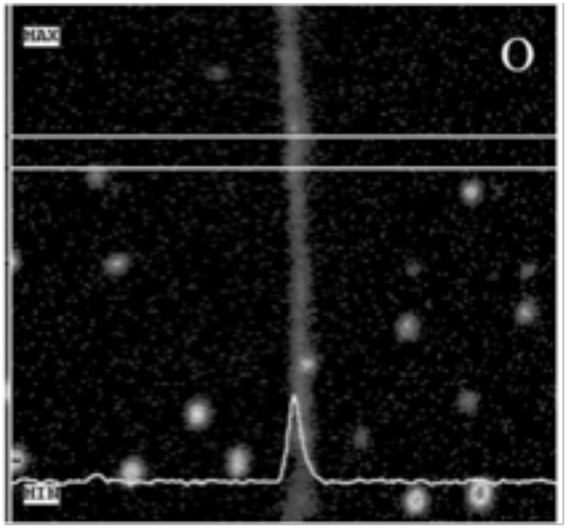
Cold welding of ultrathin gold nanowires

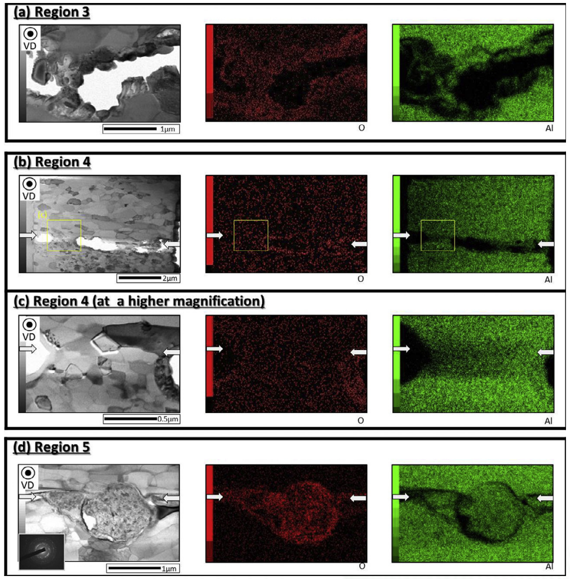
Yang Lu[1], Jian Yu Huang[2], Chao Wang[3], Shouheng Sun[3] and Jun Lou[1]*

OXIDE DISPERSION IN OTHER SSW: Not very well understood phenomenon

- Characterization showed that the films are Mg rich and forms a new oxide. in FSW the oxides that are present are not pre existing oxides but new oxides form at the interface
- In UAM there is evidence to suggest the presence of an oxygen rich zone at the interface
- Explosion welds also report the presence of oxygen at the interface

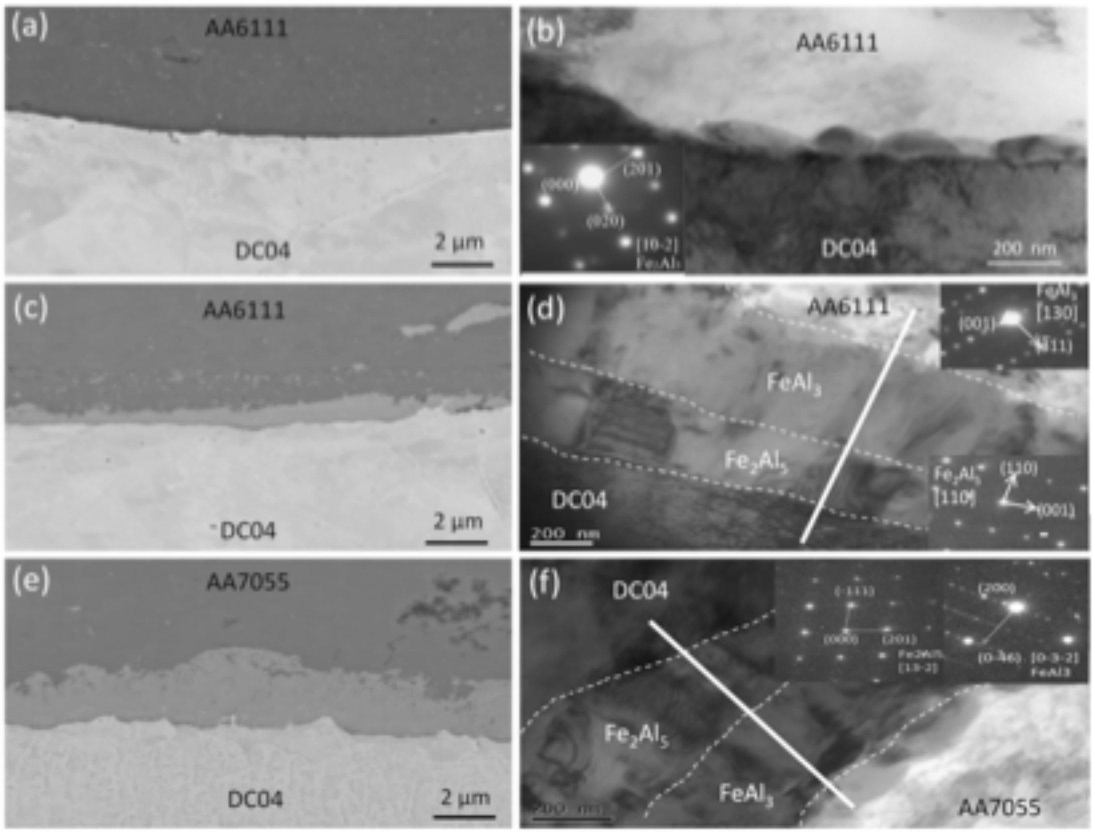


Work from Cantin et.al (2009) showing the oxygen and Mg rich zones at the interface of friction stir welded interface between Al-6061 and steel

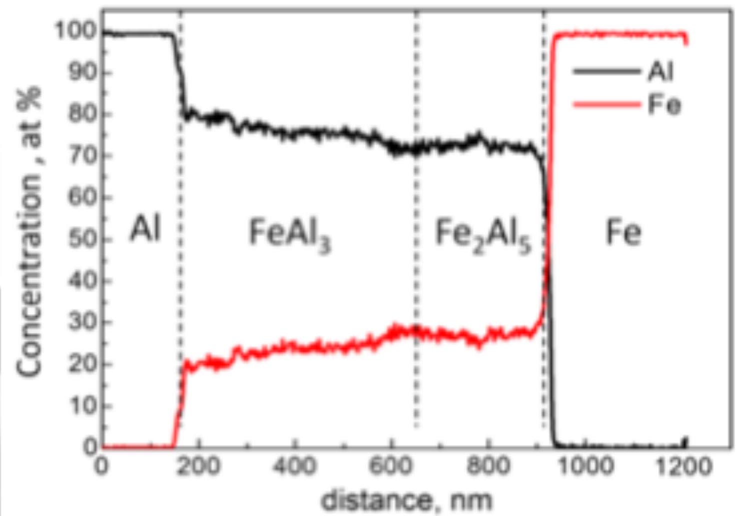


Work from Schimzu et.al (2009) showing the oxygen rich zones at the interface of Al-6061

QUESTIONS THAT WILL BE ANSWERED: The influence of jetting on oxide film disruption and the inter diffusion zone formation are not very clear and to date no characterization at the atomic scale has been performed



TEM micrograph of interfaces fabricated using ultrasonic welding welded with a welding time of (a) 0.3s (b) 1.5s (c) Al-7075 with a welding time of 1.5s (Xu et.al, 2016)



Explosive welded interfaces contain

- Al_6Fe
- Al_3Fe
- Al_2Fe
- AlFe

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So what are the unanswered questions?

Oxide dispersion and interfacial structure evolution during solid state welding. To answer these questions characterization at the atomic scale is warranted

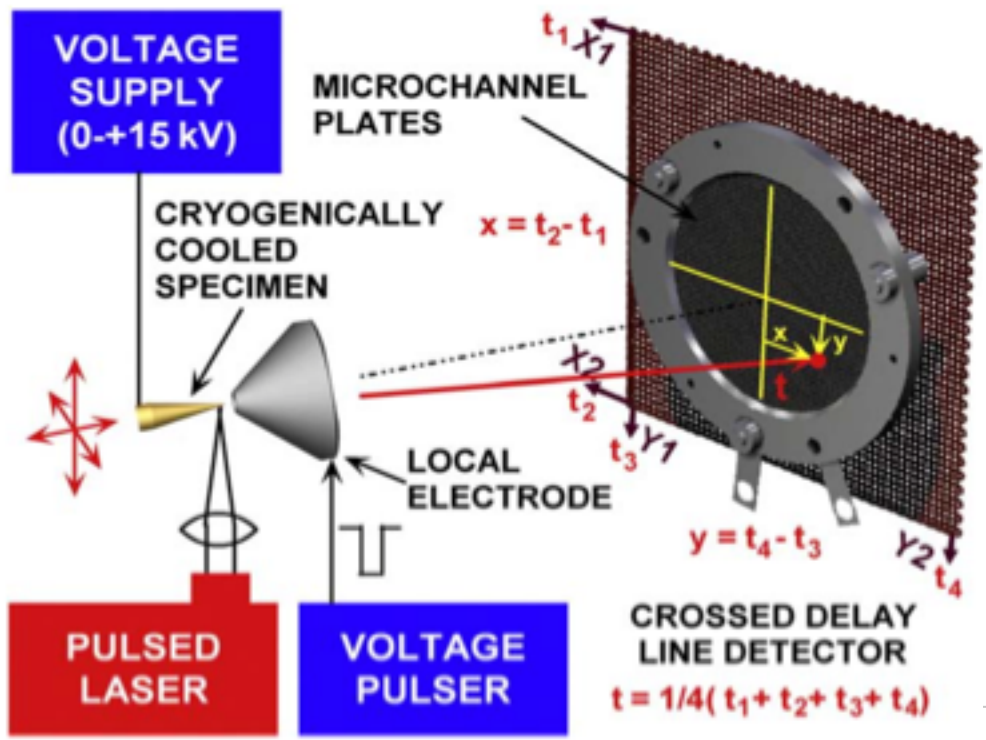
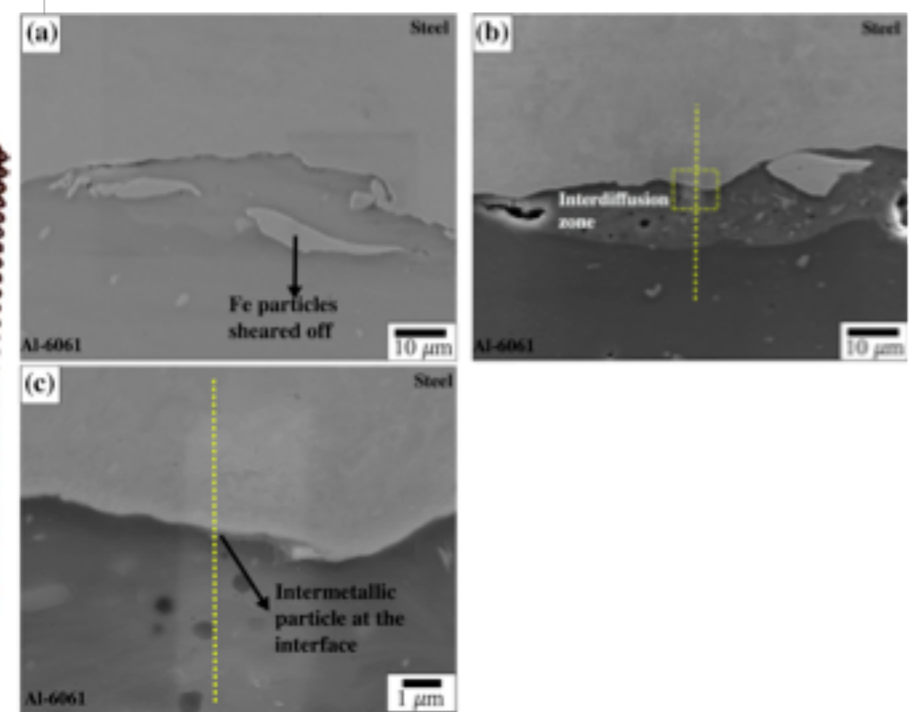
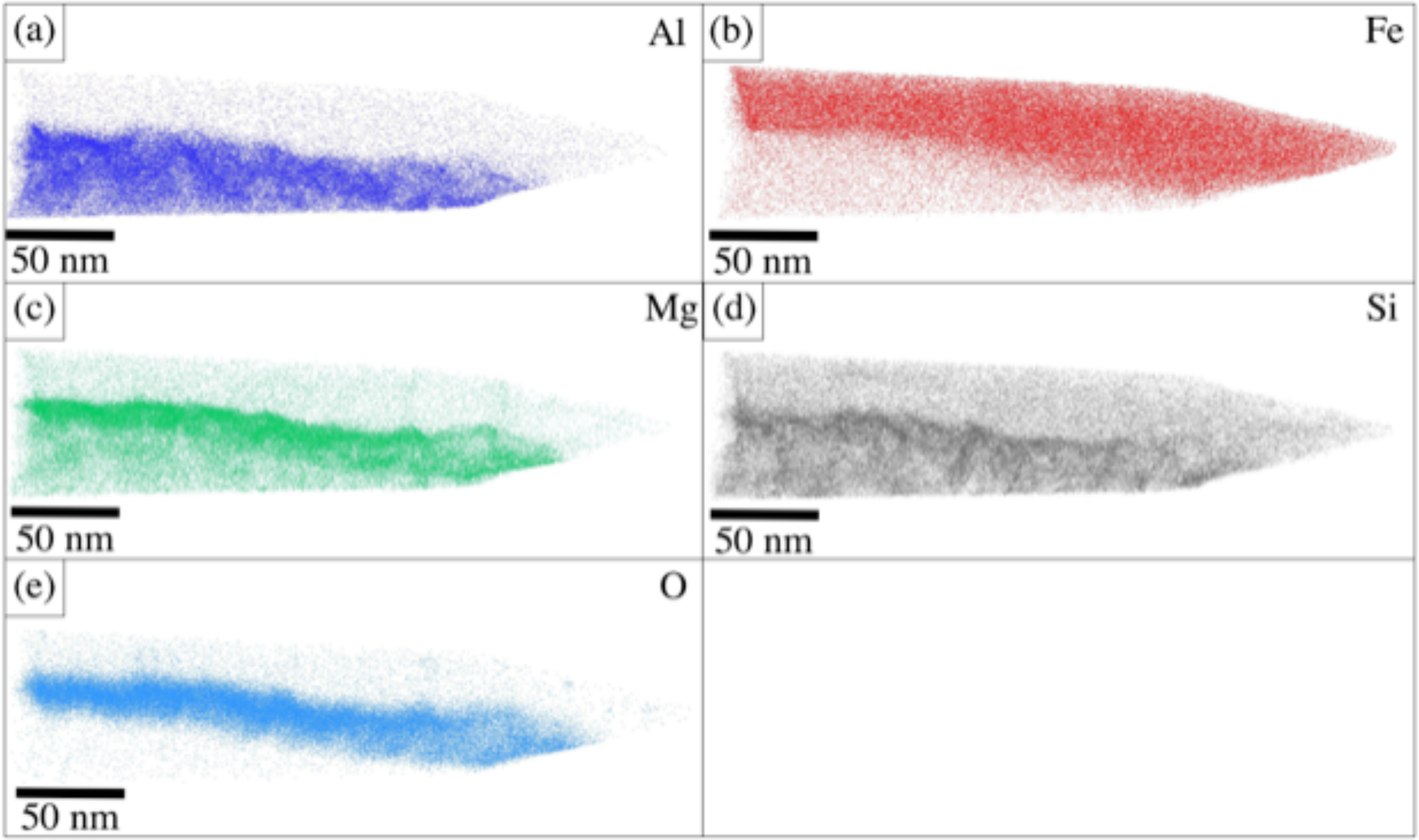


Fig. 1 – Schematic diagram of a local electrode atom probe (LEAP) with a crossed delay line single atom detector at the end of the time-of-flight mass spectrometer. Both voltage and laser pulsing modes of field evaporation are shown.

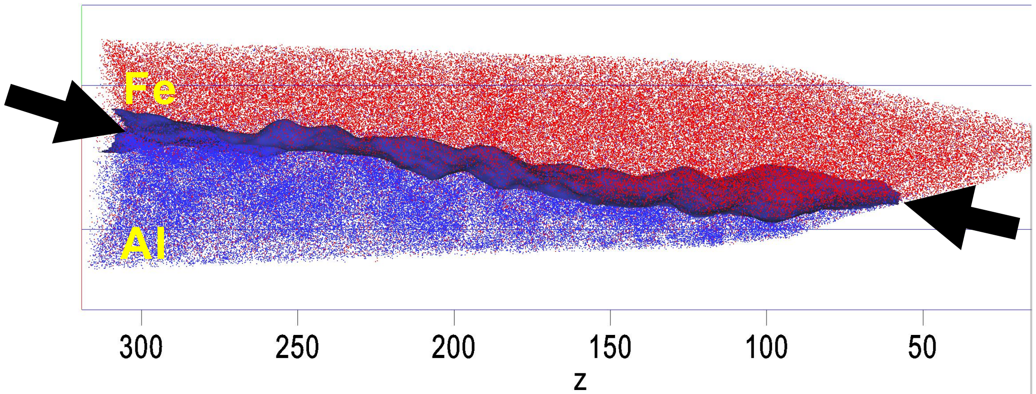


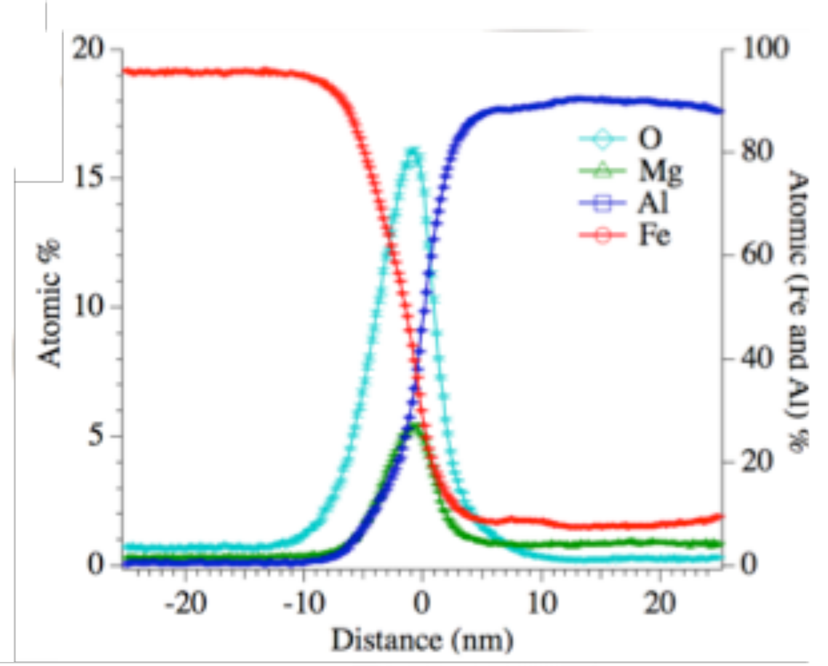
Reconstructions clearly show a significant enrichment of oxygen and Mg at the interface



QUALITATIVE MEASUREMENTS SHOW THAT THE OXYGEN ENRICHMENT IS CLOSE TO ~20 AT%:

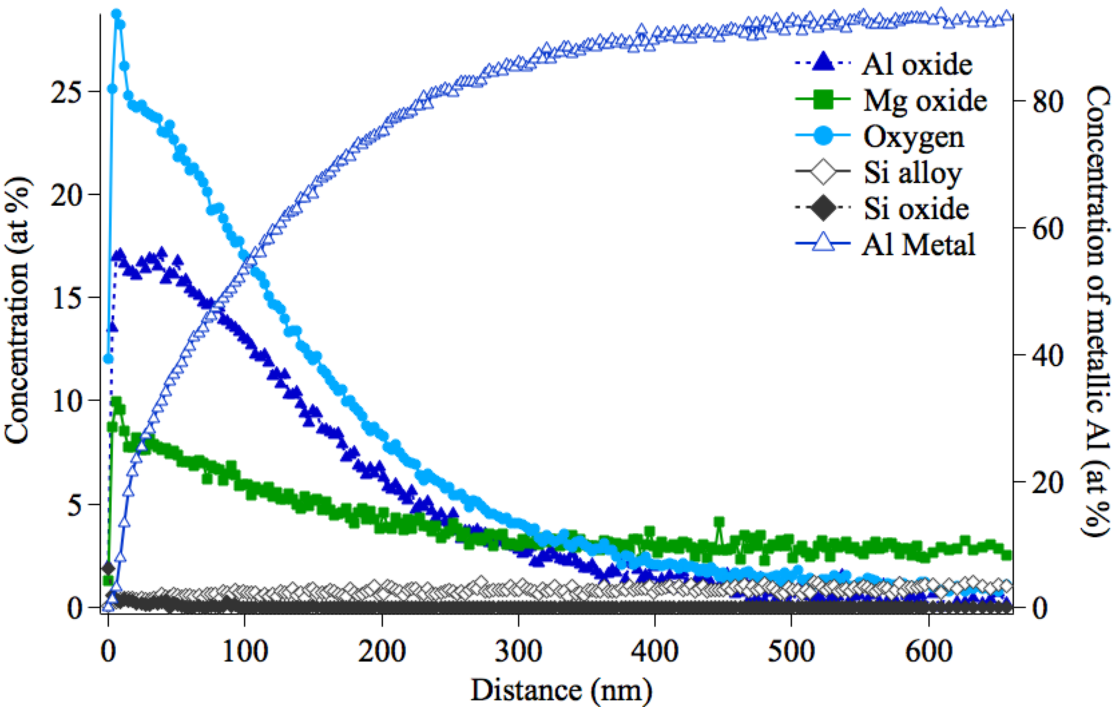
The Oxygen and Mg concentrations are much lower than those required to form stable oxides





Where does the Mg come from?

X_RAY PHOTOELECTRON SPECTROSCOPY USED TO STUDY THE SURFACE OXIDE CHEMISTRY BEFORE WELDING: Measurements show that the surface oxide is enriched in Mg



Condition	O	Mg
Current work impact welding	15 at %	5 at%
Hot rolled	30 wt%	1.2 wt%
Hot rolled+ Annealed	70 wt%	2 wt%
Cold rolled	30 wt%	0.6 wt%
Oxidation of Al-2.5 at% Mg at 400˚C in dry air for 1 hour	50 wt%	40 wt%
Oxidation of Al-0.4 at% Mg at 550˚C for 5 hours	50 wt%	50 wt%

What about the subsurface chemistry? Intermetallic formation at the interface

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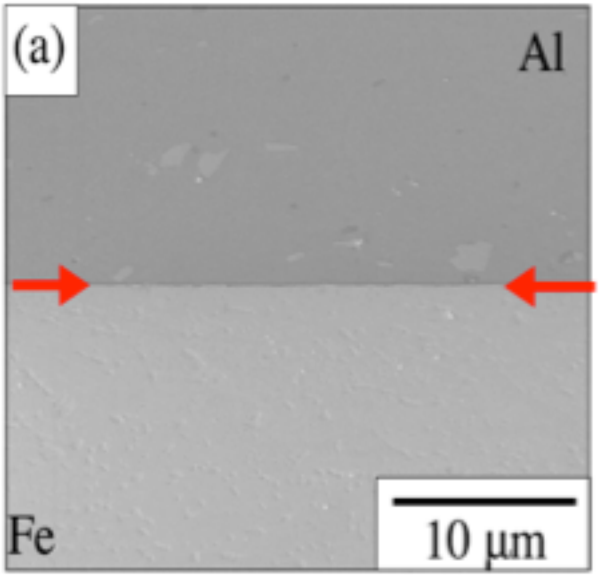
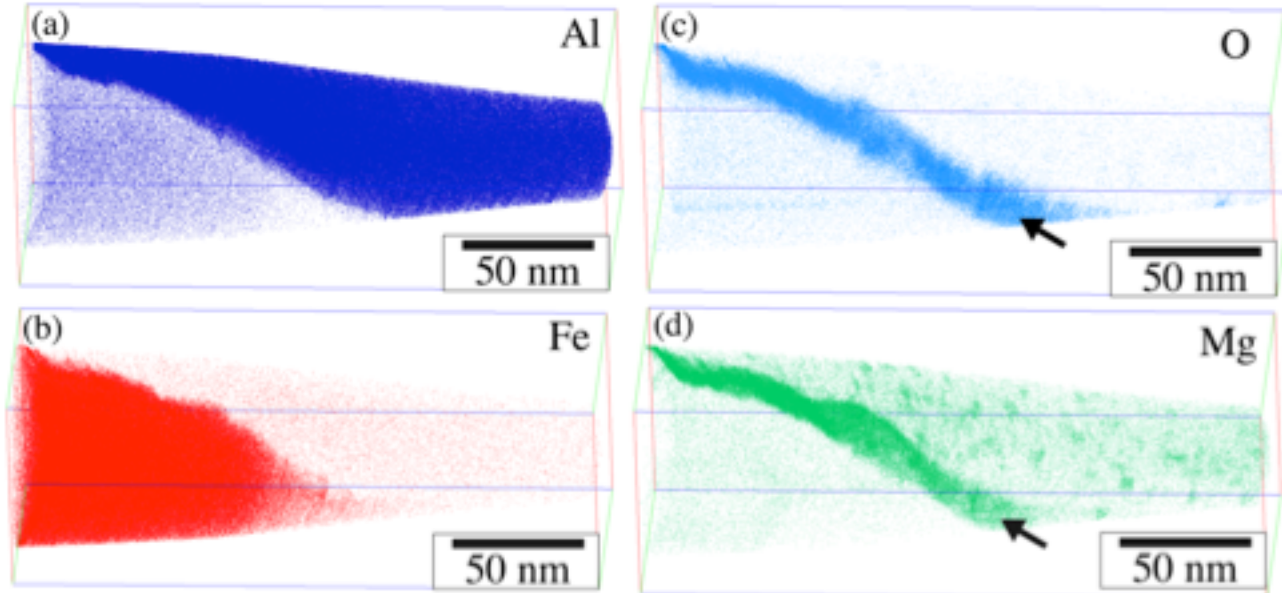
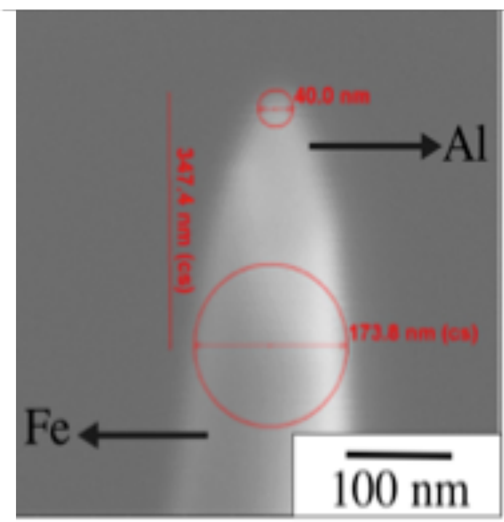
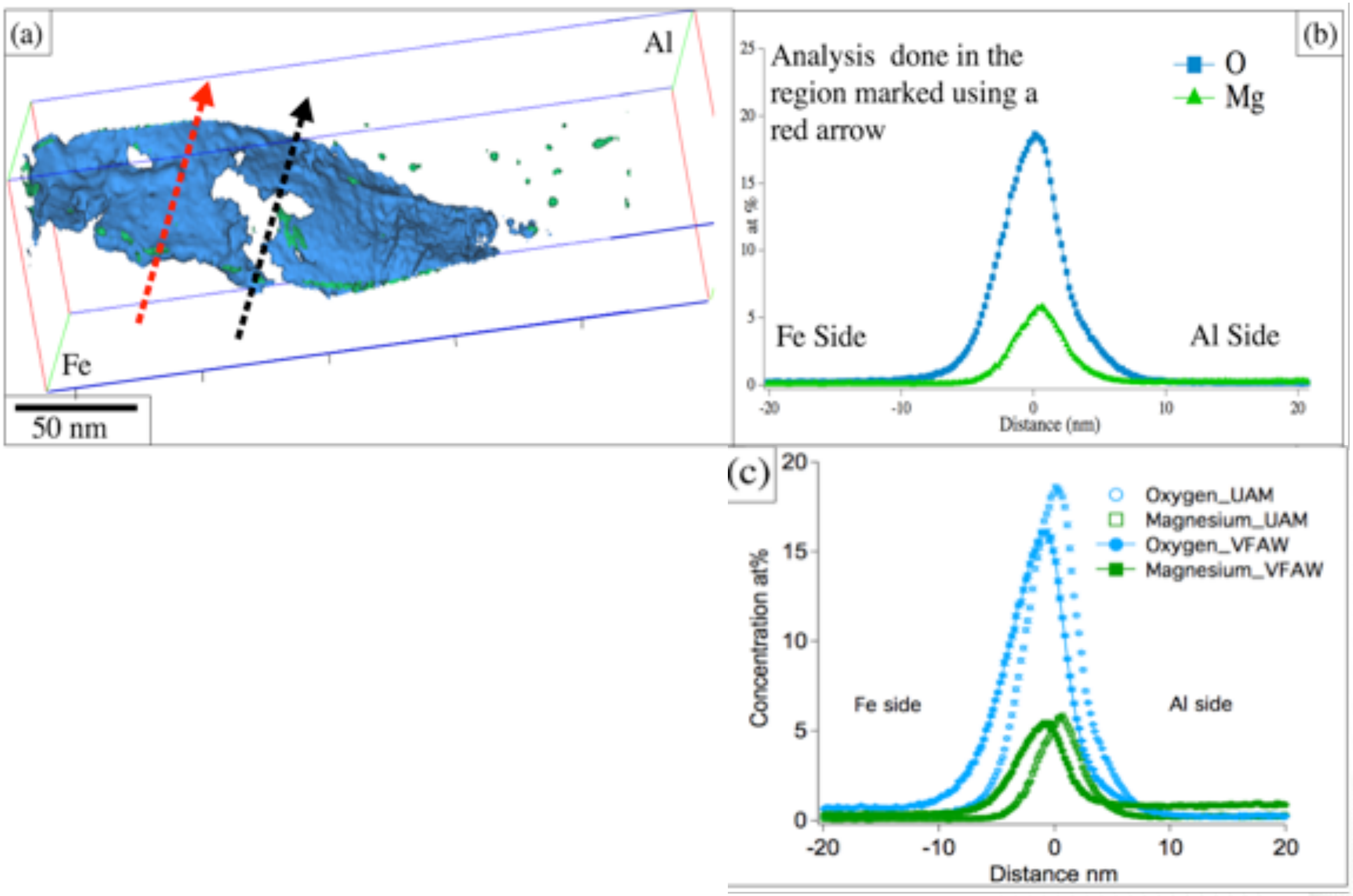
APT SHOWS EVIDENCE FOR SIMILAR MECHANISMS WHILE WELDING AL-STEEL USING OTHER SOLID STATE WELDS



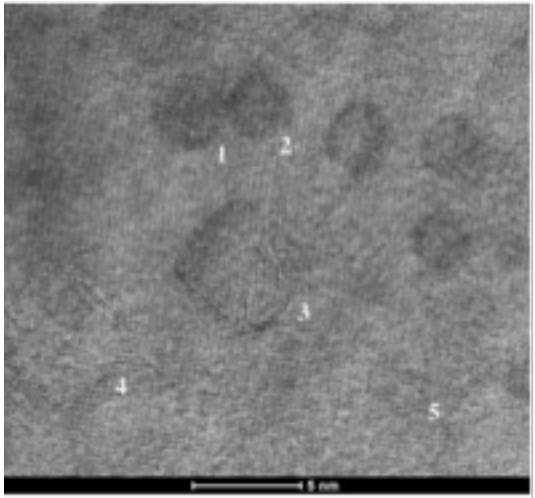


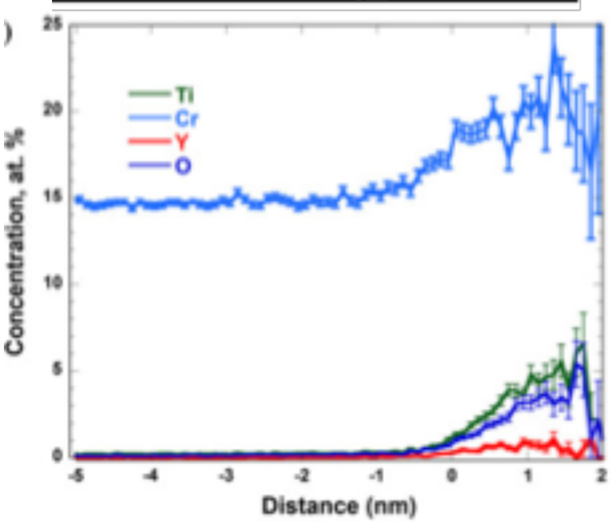


Synergies: Quantitative analysis shows identical composition profiles in the interfaces of welds fabricated using UAM and VFAW

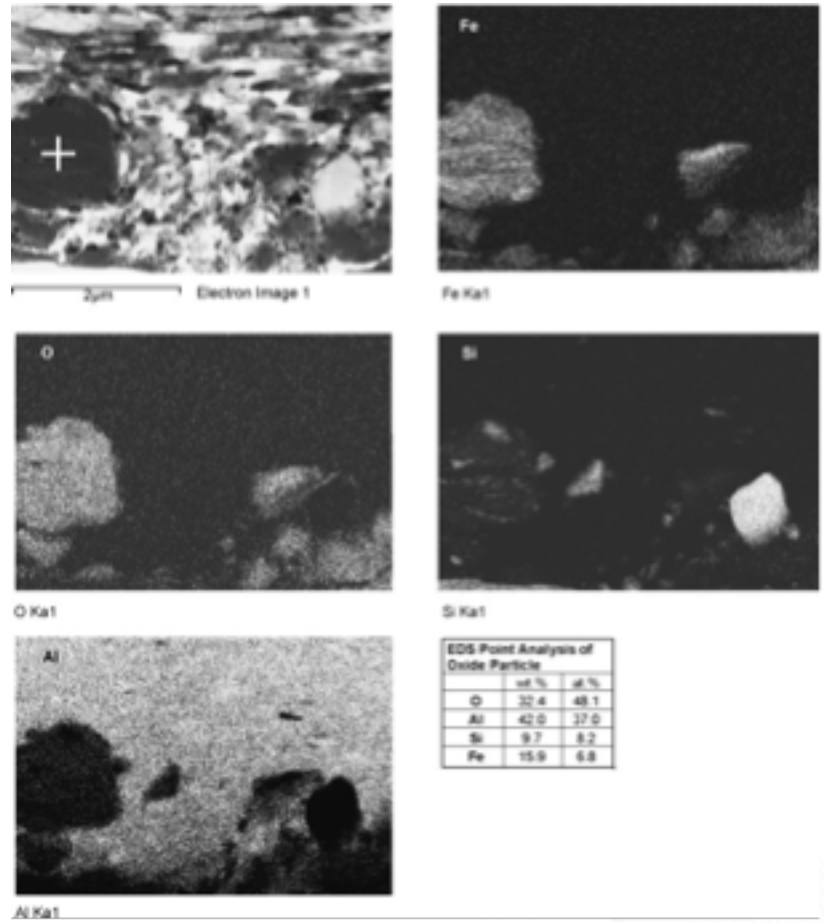


Where have similar observations been made? Oxygen dissolution from the oxide layer is well documented in ODS steels fabricated using ball milling and tribologically transformed surfaces





Atom probe specimens extracted from these nano clusters (Brandes et.al, 2012)



EDS Point Analysis of Oxide Particle		
	wt %	at %
O	32.4	48.1
Al	42.0	37.0
Si	9.7	8.2
Fe	15.9	6.8

Presence of oxygen in the tribo material in Al-Steel wear tests (Alpas et.al, 2006)

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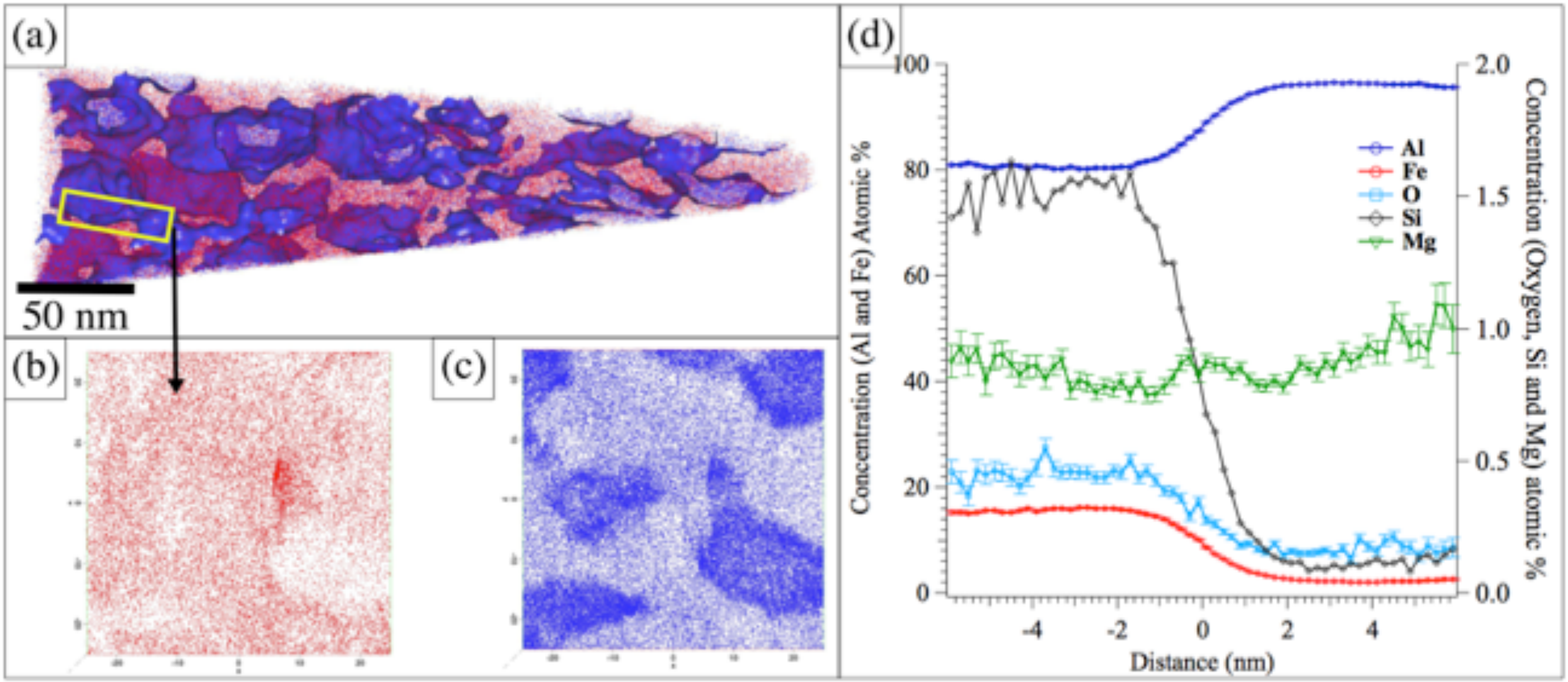
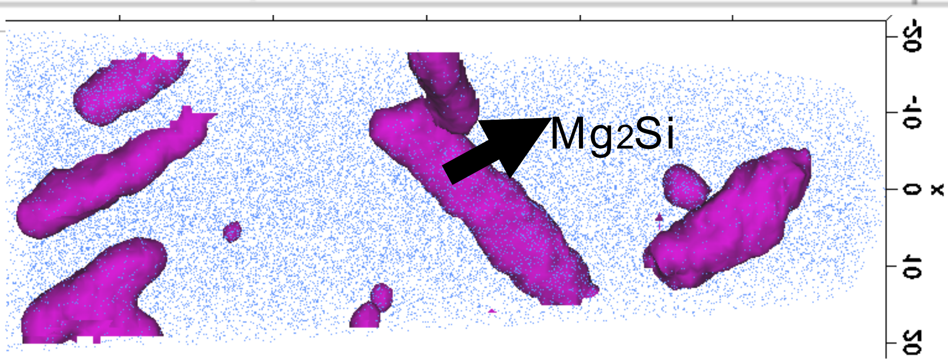
SUBSURFACE CHARACTERIZATION: Significant super saturation of Fe in Al and dissolution of the strengthening Mg_2Si phases. Could arise from a synergistic effect of deformation and temperature rise



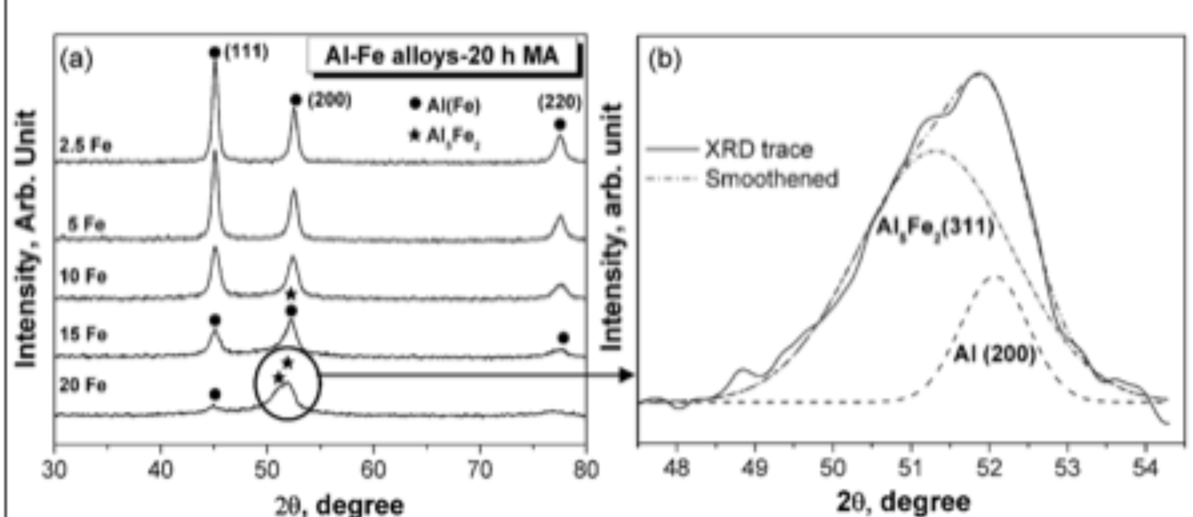


- Note the dissolution of Mg_2Si strengthening phases after welding

IMC OR SOLID SOLUTION? Compositions are contrasted with known intermetallic phases forming at the Fe-Al interfaces

Symbol	Composition
β	AlFe
κ	$AlFe_3C$
η	Al_5Fe_2
θ	$Al_{13}Fe_4$
τ1	$Al_2Fe_3Si_3$
τ2	Al_3FeSi
τ3	Al_2FeSi
τ4	Al_8Fe_2Si
τ5	$Al_{4.5}FeSi$
τ6	$Al_4Fe_{1.7}Si$

- This supersaturation of Fe in Al has been observed after high energy ball milling of elemental Fe and Al powder during ball milling



- Results from Nayak et.al showing the nucleation of ***Al_5Fe_2*** phase during MA of Al-Fe powder when the Fe content exceeds 10 at%

- At present it is not clear if this is an intermetallic reaction between molten Al and solid Fe or is just mechanical mixing

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SUMMARY AND UN ANSWERED QUESTIONS:

Evidence for oxide decomposition and dissolution of Fe in Al were observed. However there is no clarity as to how these influence the bond formation and bond strengths at a fundamental level

Disruption of the oxide surface film

- The exact nature of the Oxygen and Mg rich region at the interface is not clear. Could be
  - Solid solution
  - Non equilibrium oxide

Solid solution and deformation effects

- The enrichment of Fe and in Al. Is it a
  - Solid solution or
  - IMC
- The dissolution mechanisms and kinetics of dissolution of phases at the interface

WE NEED SUPER HEROES LIKE "*CHARACTERIZATION MAN*" TO ANSWER QUESTIONS AT THESE LENGTH SCALES

THANK YOU

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