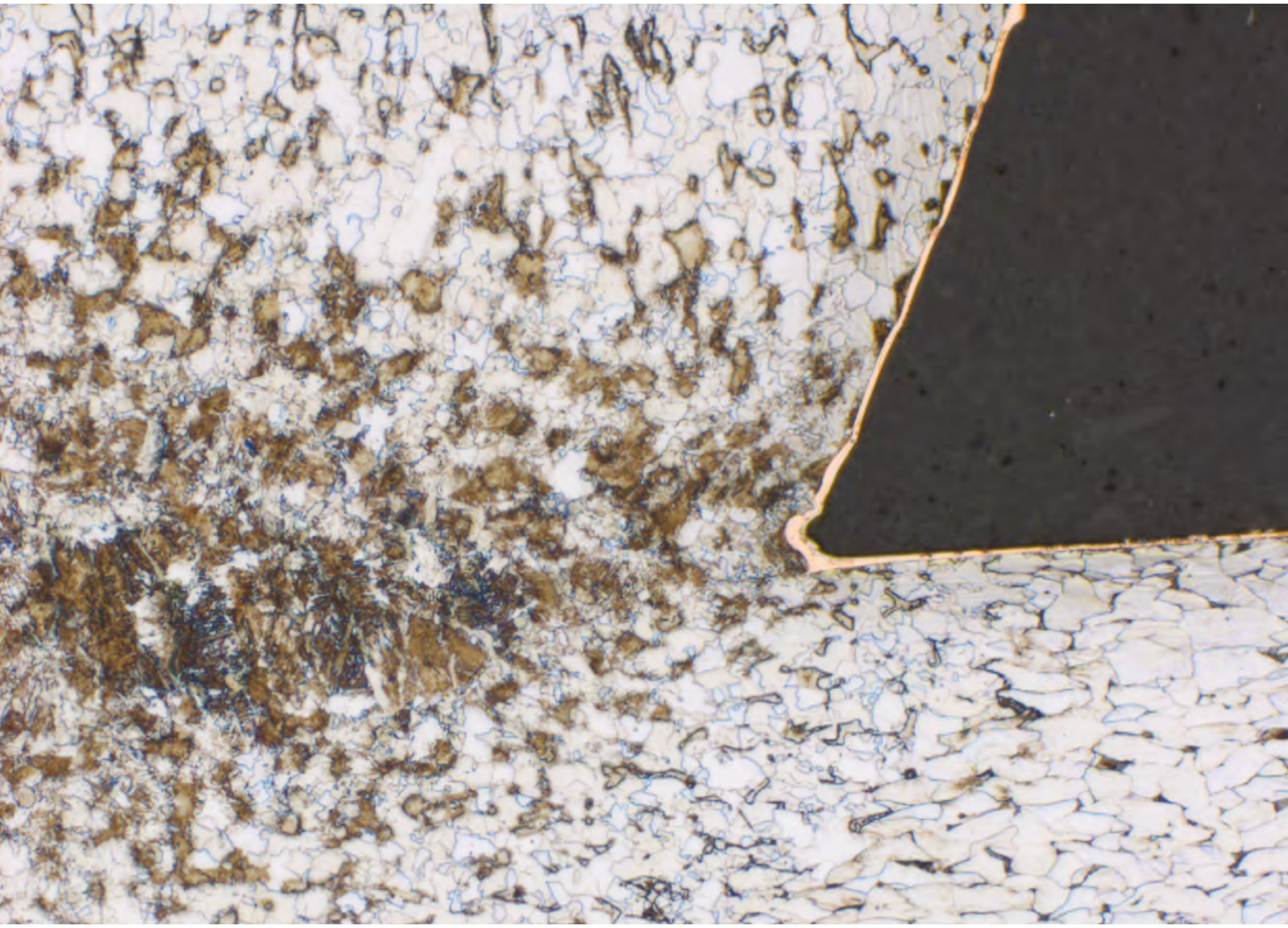
Application Note



# Physical, chemical and crystallographic analysis of metal welds

ZEISS Microscopy solutions for metallography

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## ZEISS Microscopy solutions for metallography

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**The creation of strong joints between metal components is integral to modern industry. Length scales range from pipelines in the kilometers to electronics wiring in the micrometers. Welding is prevalent throughout the modern world, from initial stages of steel production to manufacture, cladding and repair of finished components. However, as the geometry, chemistry and microstructure of joints can differ wildly from the surrounding bulk material, they are often the weakest point of any structure.**

**To mitigate the risk of failure and ensure that all parts function as required, an understanding of the joining behavior and joint properties is needed, while also maintaining excellent quality control. Combined with mechanical and in-service testing, microscopy is a key tool in the monitoring of existing welding processes and the development of new ones.**

### Introduction

Welding is a highly complex engineering discipline; there are many factors that control weld quality particularly the welding technique used, materials involved, joint geometry, and cleanliness of materials and shielding gas.

Most automated or production welding operations follow pre-defined procedures; once developed and validated these procedures are replicated on all subsequent joints. Defect formation is always possible even with established procedures and the operator must be vigilant in their quality control. A welding defect can be defined as any one of an extremely large variety of flaws or features that threatens the integrity or usefulness of a weld during its specified service. Defects take many forms including but not limited to pores, various types of cracking, lack of fusion, lack of penetration, distortion/deformation and incorrect dilution levels.

Defects do not necessarily mean a weld is unserviceable; it depends on the number, size, type, shape and position of features. For example, a tiny pore in the center of a large weld is unlikely to pose a problem, but a crack in the same weld could lead to catastrophic failure. The metallurgist must judge defects according to the joint specifications, intended service and customer requirements.

The key to understanding the weld and thus reducing defect formation to acceptable levels is to choose the correct microscope, the correct imaging mode and most effective analysis.

### Distortion

Almost all welding methods involve melting metal at the site of the joint (often with an appropriate welding consumable) leading to shrinkage during cooling. This can lead to residual stresses and distortion, depending on the joint geometry. Stressed regions are often more susceptible to corrosion and/or cracking while distortion leads to a mismatch between the required and actual component shape. Careful selection of welding parameters can mitigate this, as can clamping combined with post-weld heat treatment to relieve stress. Alternatively, if the system is well understood, the workpiece can be positioned such that a known, predicted distortion causes the item to ‘distort’ into the correct shape.

Rapid generation of 3D maps of welded regions allows a quantitative assessment of distortion, useful for optimization of joint geometry and welding parameters, as well as a quick assessment of the weld quality.

Taking plate-plate welds, also known as butt joints, as an example, there are several possible types of distortion including transverse shrinkage, angular distortion and longitudinal shrinkage.

A ZEISS Smartzoom 5 digital microscope was used to scan a test coupon weld in 3 mm thick nickel alloy plate. A 3D map was then plotted using the ConfoMap™ software, Figure 1. From this, the height of the weld root above the parent material was determined to be <0.7 mm and it was verified that the angular distortion was below 3°, Figure 2.

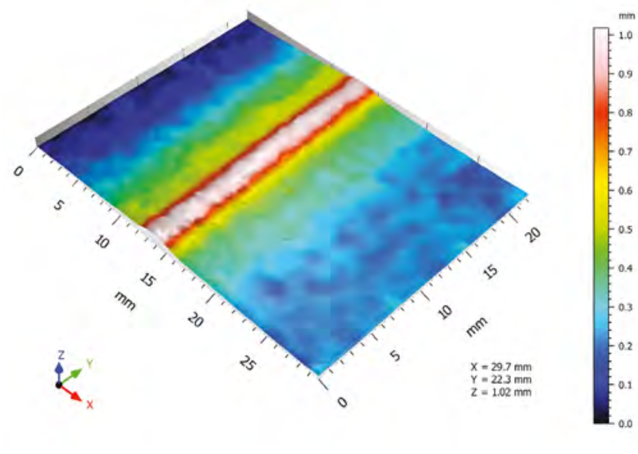
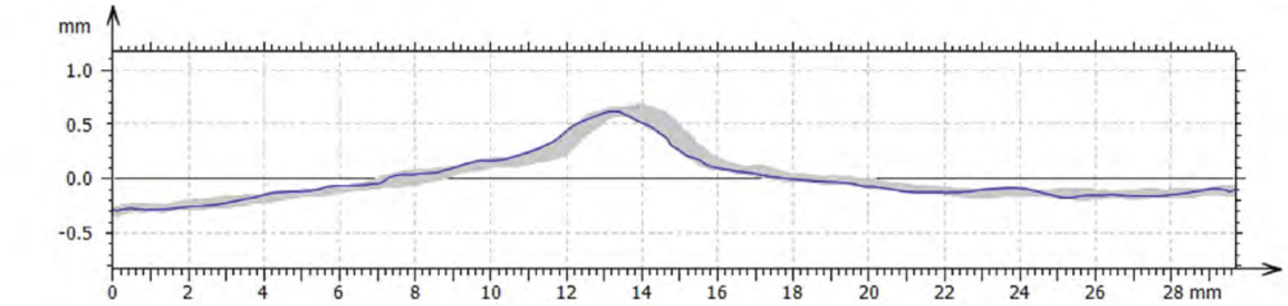



*__Figure 1__ 3D height map of root of autogenous TIG weld in Hastelloy C-276® nickel superalloy taken using a ZEISS Smartzoom 5 (LENS) and plotted in ConfoMap software. Sample courtesy of Haynes International, Ltd.*




| Information | |
|---|---|
| Profile | MET-37 Weld Root (Smartzoom) > Leveled (Least squares method) (1 / 3369) |
| T-axis | Y-axis = 0.00 mm |

| Parameters | Value | Unit |
|---|---|---|
| Length | 29.7 | mm |

*__Figure 2__ Average of all profiles across weld (X direction in Figure 1), over the entire 22.3 mm length, assessed using ConfoMap software. Angular distortion estimated by taking the average straight line profiles in the 0-9 mm and 20-30 mm regions (on the X axis) and calculating their relative angle. Sample courtesy of Haynes International, Ltd.*

**Welding defects**

Pores are a common weld defect; their number, size and position are dependent on the welding parameters. If large enough they can pose a threat to the joint integrity. Typical causes of porosity include contaminant material in the weld, contamination by the atmosphere or an improperly cleaned workplace surface leading to gas formation/entrapment in the weld. ZEISS ZEN 2 core Multiphase and Interactive Measurement software modules enable a user to characterize pores by size, shape or overall volume fraction. This assists an operator in identifying the root cause of the porosity or simply as a useful method of routine monitoring and quality control.

Using a ZEISS Axio Imager.Z2m reflected light microscope, a large pore in a weld in a nickel Alloy 625 component was located and imaged. For comparison, a section taken from a nickel Alloy 825 casting was assessed using ZEISS Sigma 300 scanning electron microscope using the high definition backscattered electron detector (HDBSD) for optimal low kV composition-based imaging.

Cracking is another common defect in welds and bears similarities to cracking observed in castings. For example, hot cracking, also known as solidification cracking, occurs in the fusion zone of a weld or in the bulk of a cast, a. Spaces between solidifying metal regions open by means of shrinkage strains where due to local shortage of liquid metal, spaces cannot be filled and hot cracking can occur. It can be mitigated by manipulating the molten metal solidification by several methods, such as altering the weld metal composition, reducing strain on the weld pool by better welding parameters or joint design, or by means of better mold design and controlled cooling.

Incomplete penetration is observed when the first weld bead does not begin at the root of the weld groove. It may be found together with lack of fusion, where the weld bead does not adhere to the base metal properly. This defect type tends to occur due to poor adherence to the welding procedure, leading to channels and crevices forming at the root of the weld. The local cross-section of the material is smaller, and the features can act as a stress concentrator for cracking, furthermore these crevices can post a substantial risk of failure in aggressive service as they are far more susceptible to corrosion.

A commercial welded component was examined using ZEISS Axio Imager.Z2m (Figure 4). The component had a weld between two ferritic steel rods, with bevels machined onto one rod to produce a suitable weld geometry. A two-layer coating covered the entire sample, a thinner reflective coating and a thicker bond layer. The weld was not symmetrical and a clear protrusion on one side, with a lack of fusion and a void between the two rods. The coating materials had not penetrated into this gap, indicating that the void was likely not surface-breaking. As this component was not intended for demanding service, the defect was considered minor and not a threat to integrity.

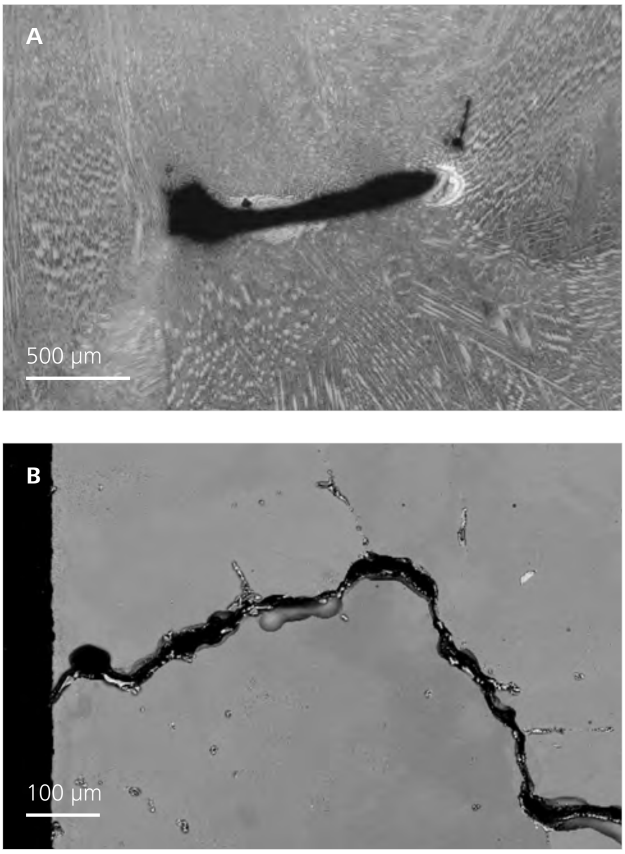



***Figure 3*** *(A) Example of welding defect – large pore in a nickel Alloy 625 weld under ZEISS Axio Imager.Z2m light microscope. (B) Example of welding defect – solidification crack in a nickel Alloy 825 casting imaged using the HDBSD detector on a Sigma 300 SEM (right).*
*Samples courtesy of TWI Ltd.*

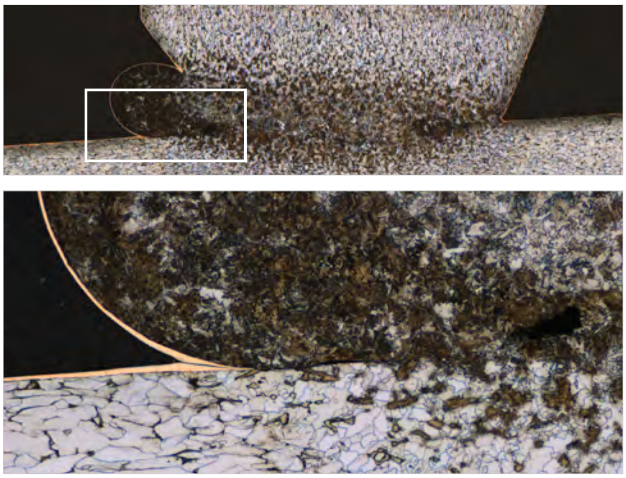


***Figure 4*** *Weld in coated mild steel component with lack of fusion on one side.*

**Dilution**

A number of applications exist where two or more different materials are present in a joint, which may be welded directly, or a welding consumable may be used, which can be slightly or substantially different in composition to either or both of the parent materials. Even use of a matching consumable does not necessarily lead to a homogenous weld composition due to elemental losses via evaporation from the weld pool or from molten droplets. For example welds in manganese-containing stainless steels may have lower manganese content than the parent material, according to ASTM.*

The fusion zone composition and microstructure (and thus the mechanical properties) are affected by the dilution, which itself is controlled by material selection and welding parameters. For a weld between carbon steel and stainless steel, the fusion zone could be austenitic which is susceptible to hot cracking. Alternatively, the weld could contain a small amount of ferrite that will help to resist hot cracking, but if diluted excessively could contain martensite, which is susceptible to hydrogen damage. It all depends on the cooling rate and the localized dilution. To properly understand a dissimilar joint and reduce failure rates, the user must understand the dilution present.

In order to explore dilution in a dissimilar joint (Figure 5), a ZEISS Sigma 300 scanning electron microscope equipped with energy dispersive X-ray spectroscopy was used to analyze a sample of high-strength low-alloy steel welded with a nickel alloy. Through the relative variation in elemental concentration, a diluted layer approximately 20 µm thick was visible in the Alloy 625 weld metal, though no corresponding layer was visible in the steel. This layer had elevated levels of iron within the dendrites and correspondingly lower local levels of nickel and chromium. This indicated partial dissolution of iron into the molten Alloy 625 during welding but that the effect was limited to the first 20 µm of the weld metal prior to solidification. Enrichment of niobium and molybdenum was visible along the Alloy 625 grain boundaries, as were precipitates rich in both molybdenum and niobium.

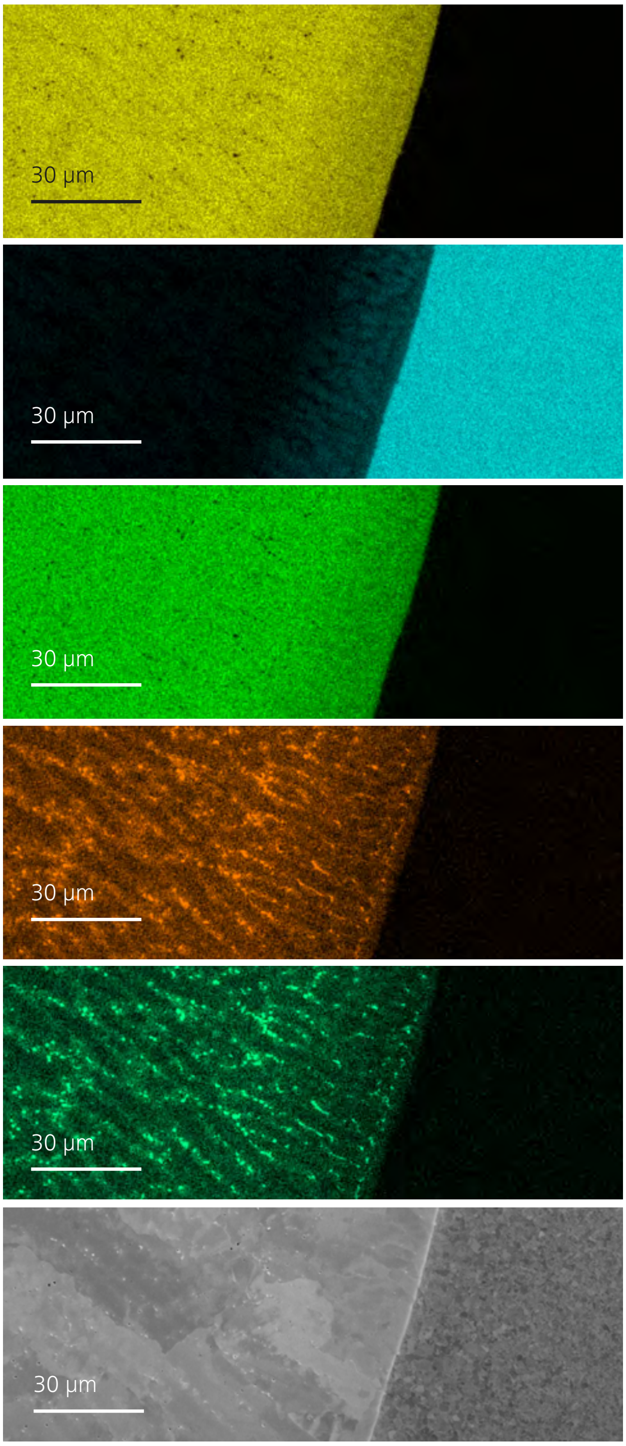



*Figure 5* *EDS map across nickel alloy 625 to 8630 steel interface, showing relative amounts of metallic elements. A secondary electron image is included for reference. Sample provided by TWI Ltd.*

*"Dilution in Fusion Welding", ASTM Handbook Volume 6A, Welding Fundamentals and Processes, pp116-121.

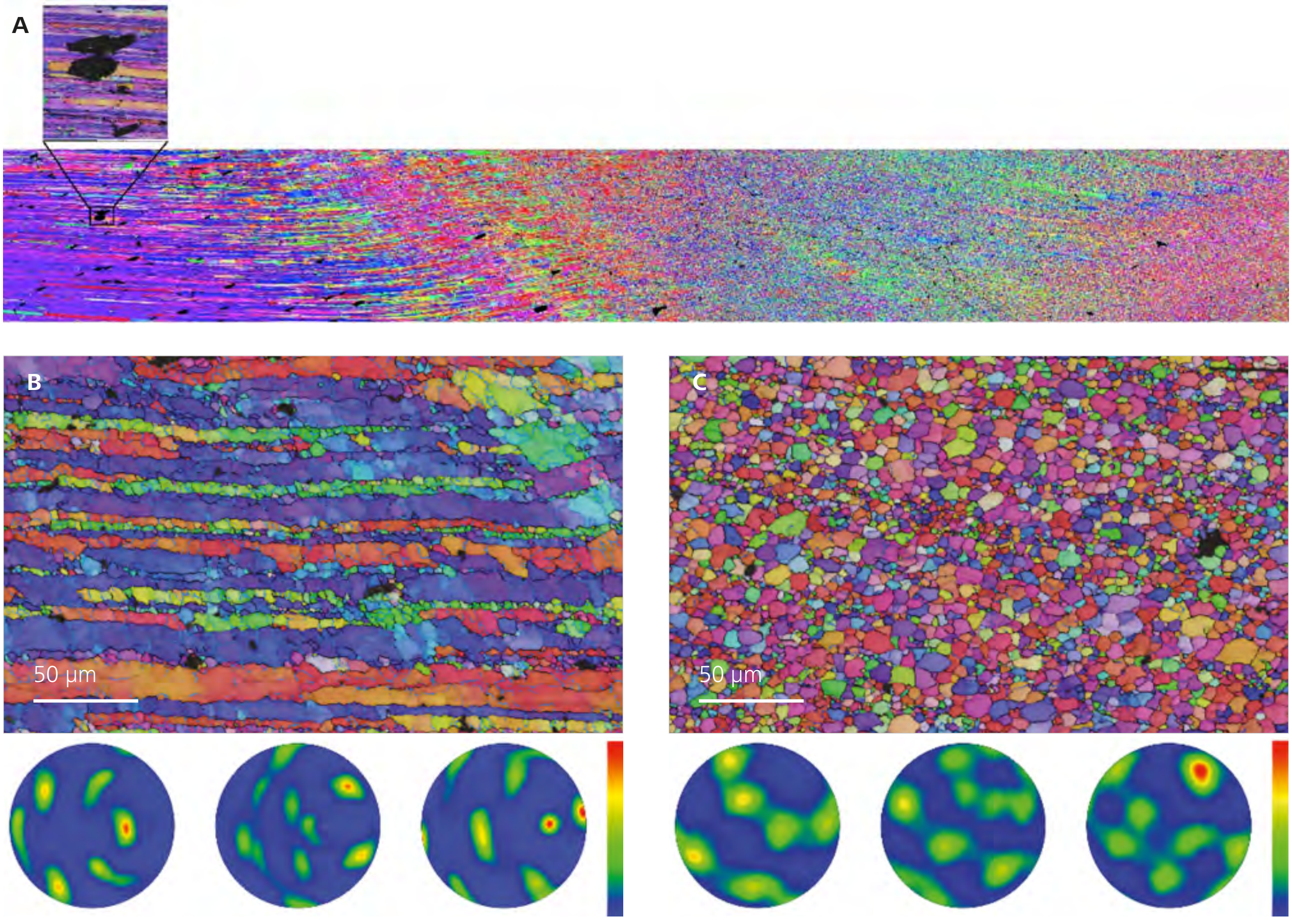



***Figure 6*** *EBSD maps of friction stir welded aluminium alloy plate. (A) EBSD map showing friction stir weld and example unregistered region. (B) EBSD map and pole figure of parent material (C) EBSD map and pole figure of the centre of the welded region. Sample provided by TWI Ltd, EBSD maps and data provided by Oxford Instruments Nanoanalysis.*

**EBSD characterization of welds**

Electron backscatter diffraction (EBSD) is an advanced characterization technique that provides information on texture and grain structure of welds depending on the crystal structure of the weld materials. Conventional methods (light and electron microscopy) give information on the shape and size of grains, but only EBSD also gives information on crystallographic orientation. With reference data, you can also obtain information on local strains and deformation. Where there is only plasticization rather than metal melting (e.g. friction stir welding), an EBSD map gives valuable information regarding the weld microstructure towards weld procedure development and prediction of joint performance.

Work was performed in collaboration with Oxford Instruments NanoAnalysis to carry out EBSD mapping of a friction stir weld in 7 mm thick rolled aluminum alloy plate. The scan covered almost the entire 38 mm length of the cross-section to include weld, transition zone and unaffected parent material, Figure 6.

The parent material is shown to have elongated grains with a clear common alignment in the rolling direction. The weld material shows a finer grained structure with a substantially different texture and will have different mechanical properties. Some small regions could not be indexed due to slight surface damage, showing the importance of high quality metallographic preparation and the sensitivity of EBSD to surface effects.

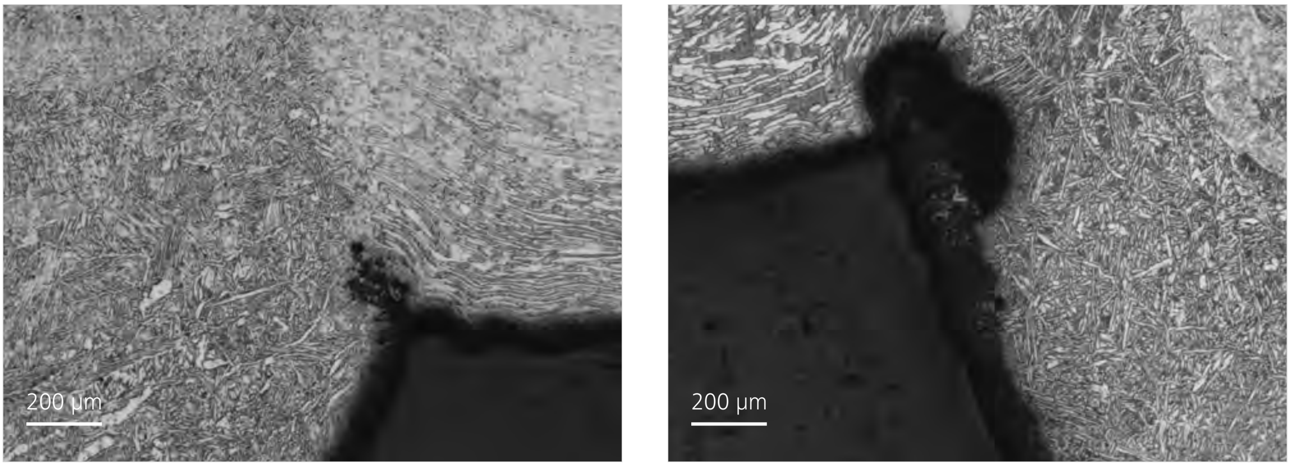



***Figure 7*** *UNS S32760 duplex steel TIG weld after corrosion testing, showing pitting and a root flaw with some limited cracking. Sample provided by TWI Ltd.*

**Corrosion flaws**

In industrial service, metal components frequently serve in harsh conditions – offshore environments, acidic and basic liquid handling or high temperature corrosive gases, where materials performance is more challenging. This can be mitigated by appropriate material selection (e.g. corrosion resistant steels), using protective coatings, cathodic protection or by increasing thickness (a corrosion allowance) to provide for a specified lifetime.

While a material may resist a particular environment, engineers must ensure the joint does too. Sensitization, hydrogen embrittlement, residual stress, local compositional changes and geometric imperfections (crevices) are all possible outcomes of welding and may lead to mechanical failure in service or heavy localized corrosion at the weld or heat-affected zone. It is often difficult to discover why a specific weld corroded without detailed microstructural examination. A corrosion experiment was performed on a duplex stain-less steel joint (UNS S32760, U-prep, welded using TIG and matching consumable). Using ZEISS Axio Imager.Z2m in brightfield mode, minor corrosion was observed at the weld root on one side, penetrating approximately 200 µm into the weld.

On the other side of the root, the corrosion was far heavier. A crack had initiated into a region that was potentially of different composition to the rest of the weld, as evidenced by its differing behavior under etching. The overall weld shape did not suggest insufficient penetration, but the corrosion behavior clearly confirmed the presence of root flaws and that the weld was unsuitable for service in these conditions. This feedback is key for quality assurance and good welding procedure design.

**Welding procedure development and qualification**

A large percentage of routinely applied or production welds follow a tight set of requirements, known as a welding procedure specification (WPS). Each joint will have its own WPS, with potentially different welding parameters depending on material type, size, thickness, welding consumable, welding process, joint geometry and intended service of the component. The welding procedure, operator and facility must also be qualified to the applicable standard, with validation testing including both non-destructive and destructive testing. The specification will likely include requirements for joint preparation as well as cleaning and processing after welding, such as grit blasting.

ZEISS light and electron microscopes can be used both during development and qualification of a welding procedure, as well as for routine QA checks of sample welds. Additionally, it is possible to use ZEISS ZEN 2 core software to set specific controlled workflows for the routine analyst, ensuring adherence to microscopic procedures. Welding defects (as described above) can be located. Assessment of the microstructure gives information on the joint performance – non-metallic precipitates, grain growth, the balance of phases, the size of the heat affected zone and the bead configuration all affect performance in service and can be controlled during welding.

As an example, the balance of austenite and ferrite in duplex stainless steel affects the local properties. Too much ferrite in a weld may lead to a loss of ductility/toughness, but too little reduces the resistance to stress corrosion cracking – manipulation of this ratio is achieved by controlling heat input, consumable choice and weld geometry.

A super-duplex stainless steel weld was examined using ZEISS Axio Imager.Z2m. Under brightfield imaging, different austenite:ferrite ratios were clearly visible in the parent material and the weld. Provided the sample was appropriately etched, the austenite and ferrite could be easily segregated to determine the appropriate fraction of each.

Use of the ZEISS ZEN Intellesis machine learning tool for advanced intelligent image processing greatly enhanced the quality of the segmentation (Figure 8) as it can assess multi-channel data and recognize areas by texture as well as greyscale and/or color contrast.

This powerful method is applicable in a variety of industries and other related use cases – determining pearlite fraction in ferritic steels, porosity in a coating (via ASTM E2109), volume fractions of alpha and beta phase in brass or even assessment of the size of a crack during failure analysis by determining the relative areas of heat-tinted fracture surface to clean fracture surface.

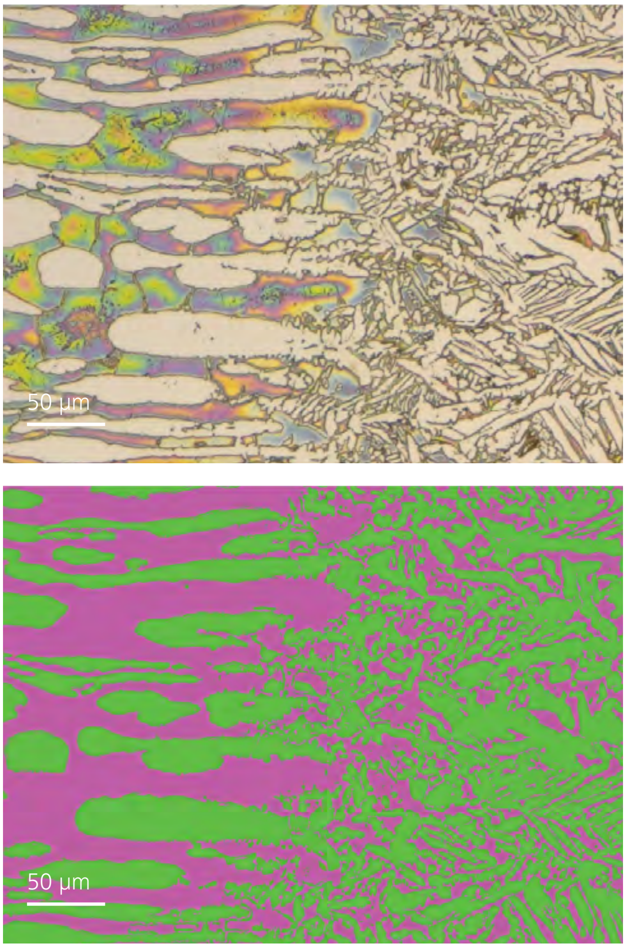



***Figure 8*** *Segmentation of austenite and ferrite at the interface between parent and weld metal, using ZEISS ZEN Intellesis machine learning system. Sample courtesy of TWI Ltd.*

## Summary

Microscopy provides a powerful tool for gathering the data needed to make critical decisions in welding, at all steps of the process through procedure development, initial trials, validation and routine quality monitoring. By selecting the right microscopy method(s), a complete picture of a joint is built, with all its microstructural features clarified. Combined with ZEISS material analysis modules for key supplementary information, using ZEISS microscopes wisely will improve the quality, efficiency and reliability of your welding processes.



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