CASE STUDY:

Smart Defect Analysis of Additively Manufactured Nickel Superalloys

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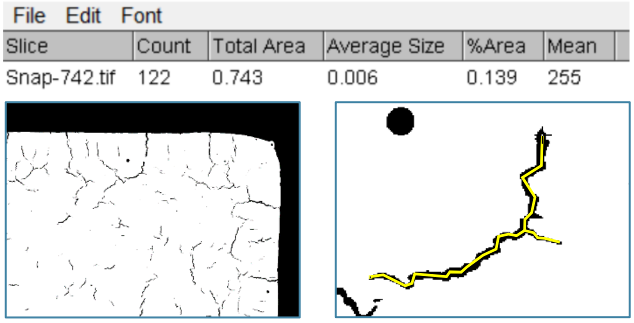
Problem Statement

Metallographic analysis of samples is a key part of OxMet's work to develop novel nickel superalloys that can be processed defect-free by additive manufacturing (AM). Being able to quantify the size and density of defects such as porosity and micro-cracking enables much greater value to be extracted than a simple "cracks/no cracks" analysis. Existing techniques for analysing cracking have been slow, labour-intensive and, most-importantly, unsophisticated. The integration of MIPAR to OxMet's workflow has allowed for the creation of smarter analysis procedures that produce in-depth, quantifiable results which, alongside the integrated visualisation tools, enable the more effective presentation of information both internally and to external clients.



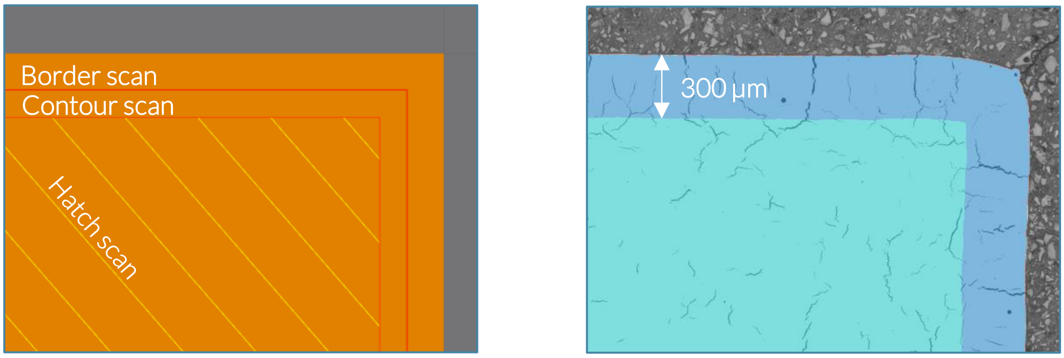
Slice	Count	Total Area	Average Size	%Area	Mean
Snap-742.tif	122	0.743	0.006	0.139	255

Figure 1: Simple data, unaesthetic images, and manual measurements are all hallmarks of existing analysis techniques

MIPAR's Solution

The nature of the AM process means that it's important to analyse defects according to where they lie within the sample, due the different process parameters used for the bulk and the border (*Figure 2*) – this way, the effect of different scans can be investigated. In OxMet's case, it was necessary to have the ability to separate defects that fell into either a Bulk region or an outer Border region which spans the outer 300 µm of the sample – both regions will undergo a different thermomechanical behaviour as a result of changing energy input. In each of these regions it's possible to find any combination of porosity, lack of fusion, or cracks.

By working with MIPAR's team to identify the difficulties in analysis and the criteria that had to be met (feature size, resolution, contrast…), a procedure was created that could effectively identify and segregate different defects according to both their nature and location within the sample.

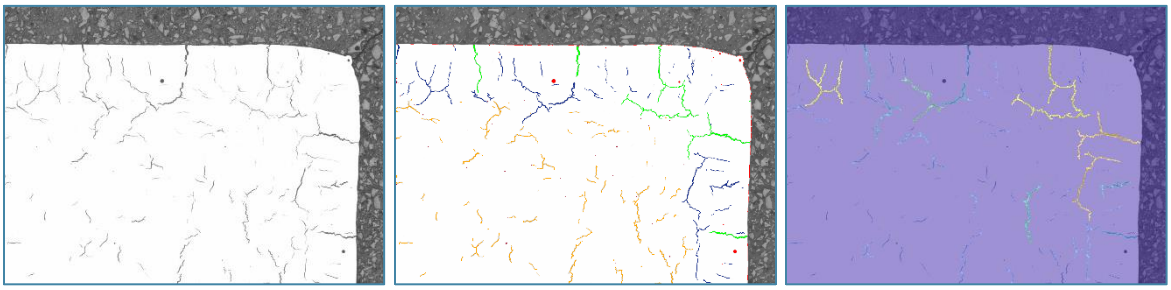


a) b)

Figure 2: a) the different scans used in an AM sample, producing different microstructures, and b) the bulk region (turquoise) and border region (light blue), corresponding to the different scan regions

The seven defects that are analysed in this procedure are named and coloured as follows:

- Bulk Porosity
- Bulk Lack of Fusion
- Bulk Cracks
- Border Porosity
- Border Lack of Fusion
- Border Cracks
- Surface Cracks



a) b) c)

Figure 3: a) Raw input image obtained from optical microscopy, b) an automatically-processed image showing defects highlighted in different colours, and c) cracks coloured according to their lengths, showing how Border and Surface Cracks are often longer than Bulk Cracks for high-strength alloys

Once all the defects are identified, the final part of the procedure runs measurements to evaluate the key properties of the sample, such as Density (measured in % solid material) and Crack Density (measured in mm of crack length per mm^{2} of sample area), such as in *Table 1*. These overall values are then used to evaluate how well the AM sample was processed, the results of which have demonstrated how OxMet's alloys can be processed defect-free whilst existing "legacy" alloys show different degrees and types of cracking. Cracks that connect to the surface of a sample are particularly problematic, since these cannot be removed by Hot Isostatic Pressing, a common post-processing technique. By designing materials that are designed specifically for the AM process, OxMet's Nickel alloys allow for the production of high-temperature components with greater reliability and performance.

An example of how MIPAR's smart defect analysis can be used to develop a component for AM is described in the following section.

Bulk Properties				**Border Properties**				**Surface Properties**
Porosity/ %	Lack of Fusion/ %	Density/ %	Crack Density/ mm mm^{-2}	Porosity/ %	Lack of Fusion/ %	Density/ %	Crack Density/ mm mm^{-2}	Crack Density/ mm mm^{-1}
0.03	0.00	99.96	1.93	0.13	0.10	99.77	9.34	0.66

Table 1: Example of measured data of a sample, showing key processing metrics such as Density/ % and Crack Density/ mm mm^{-2}

High-Pressure Turbine Blade

To investigate the effect of material choice on the manufacturability of a real-world component and fully test the MIPAR analysis, OxMet selected a small turbine blade from a helicopter engine to reverse engineer and re-manufacture using AM (*Figure 4*). The blade measured approximately 31 mm tall and is typical of the type of component that aerospace and energy industries are attempting to produce with AM. Conventionally, a high-temperature blade like this may be made from a high-performance superalloy such as CM247LC. This alloy was developed and optimised in the 1970s for components made by directionally solidified casting and, whilst it proved revolutionary for this manufacture method, modern industry has struggled to adopt it for AM parts. This is due to the vastly different heating and cooling characteristics of the process which cause significant amounts of cracking, as measured and visualised by the MIPAR process in *Figure 5 a* and *b*.

Figure 4: The high-pressure turbine blade

By varying the parameters described in *Figure 2 a*, the cracking in CM247LC can either be spread across the entire Bulk of the part or localised towards the Border region, though it is impossible to eliminate cracks entirely whilst still maintaining the economic viability of the part. There are some existing alloys that are well-suited to the AM process and show virtually no defects, such as IN718 in *Figure 5 c*, though these alloys are unable to maintain strength at the high temperatures required of modern turbine engines.

There is therefore a need for new alloys that are both high-performance *and* easily processible using AM, alloys which are designed bottom-up to be used in the AM process and will allow engineers to unlock the full design freedom offered by AM. By using MIPAR at all stages of alloy development, OxMet has been able to develop alloys with the optimal trade-off of cost, processability, and performance.

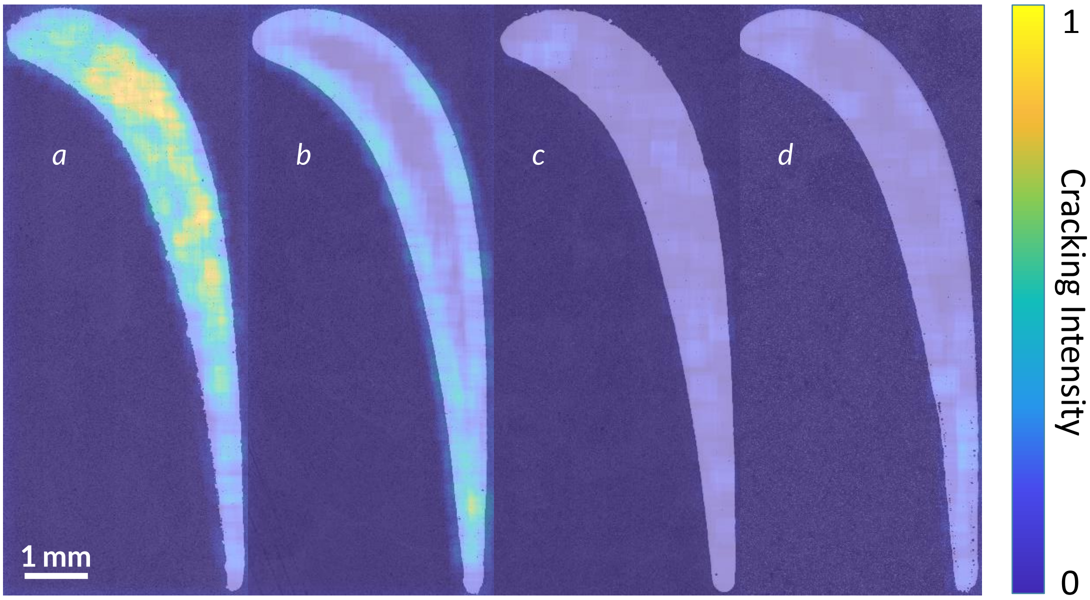


Figure 5: Sections of each AM turbine blade, showing the variation of cracking intensity with alloy. The alloys used were a) CM247LC & parameter set 1, b) CM247LC & parameter set 2, c) IN718, d) OxMet's ABD®-900AM