PLASTOMETREX

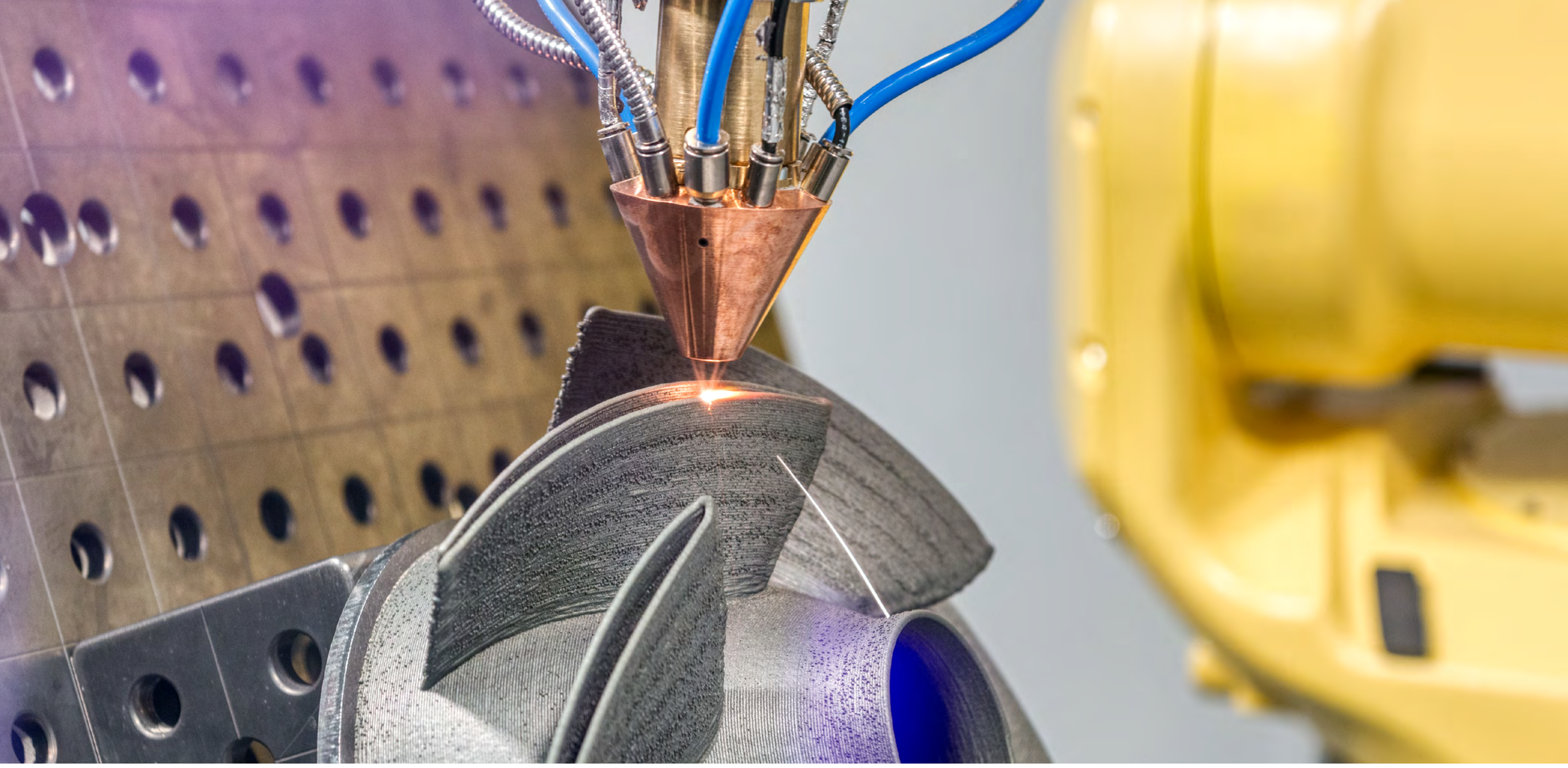
PLX CASE STUDY

Risks Unveiled

Tackling the Blindspot of High-Performance AM Parts

In collaboration with

Alloyed



Challenge

From hydraulic manifolds for F1 cars, to tertiary structural brackets for aircraft, and rocket nozzles for space shuttles, low-volume production and complex part geometries are some of the major advantages of additive manufacturing (AM) over conventional methods for high-performance parts.

To maximise performance and to ensure that parts can withstand the loading conditions required of them, these geometries often undergo a topological optimisation process, involving extensive finite element modelling.

A key input of this modelling process is the mechanical property data of the material making up the part, traditionally obtained through uniaxial testing, often with a tensile test machine. While it may be standard practice, does the conventional method of collecting this vital data actually deliver the information required to truly understand how a part will perform? Potentially not.

Uniaxial testing is performed on large testing coupons which often can't be extracted directly from the 3D-printed part. This leads to testing on separately printed witness coupons with the assumption that the properties found from these are representative of the whole component. Herein lies the problem.

The thermal history of a part depends on its geometry. For example, thinner sections of a part may cool faster than other, thicker sections, and so on. This is significant as the microstructure and mechanical properties of a part are dependent on thermal history, and can therefore vary significantly across different sections of a part, especially within the complex geometries that are so common in additive manufacturing.

This is why the snapshot provided by witness coupons may lead users to the conclusion that their part is isotropic and homogenous, and able to withstand the required loading conditions, when they may in fact be at risk of failure.

Objectives

The aim of this case study, conducted in conjunction with Alloyed, was to use PIP testing to compare the mechanical properties of a metal 3D-printed bracket to those of a witness coupon.

Witness coupons present challenges. While they provide a window of mechanical performance, the information obtained through witness coupons is only related to the gauge section of the coupon and the specific location within the AM build, and may not accurately represent mechanical performance over the entire length of the coupon or the geometry it is intended to represent.

It is also worth noting that coupons are often produced and tested to determine the expected performance capabilities of specific material and process combinations. This means that the test results aren't always reliable as the geometric factors and thickness of the coupon might not be representative of the final, produced part. This lack of correlation provides inconsistencies in the mechanical performance of a part versus expectation.

This study explores the possibility and importance of analysing materials in their true form to gain a deep understanding of the relationship between process, geometry, and materials. With PIP being able to test smaller, un-machined samples (in contrast to the requirements of tensile testing), testing can be done directly on the part itself, removing the uncertainty of witness coupons. By providing the ability to characterise property changes in complex geometries, PIP testing would allow designers and engineers to produce the desired properties in different regions of parts and increase their confidence in how a final part will perform.

Image: *A printed witness coupon*

Witness coupons may not accurately represent mechanical performance over the entire length of the coupon or the geometry it is intended to represent.

Materials

The automotive bracket and associated tensile coupons were printed in AlSi10Mg and used in this case study. The sample was provided by Alloyed, designed by Gestamp, and manufactured using laser powder bed fusion. The automotive bracket was investigated in three different regions (Figure 1) undergoing typical LPBF environmental circumstances that could affect the local mechanical performance:

- Close to the build plate, which could see the highest magnitude of annealing in a longer build.
- Aggressive downskinning, in which parameters are often adapted and defects, high residual stresses and distortions are more common.
- Vertical section further from the build plate, which could represent the bulk and therefore the expected baseline which would be investigated by extracting a coupon.

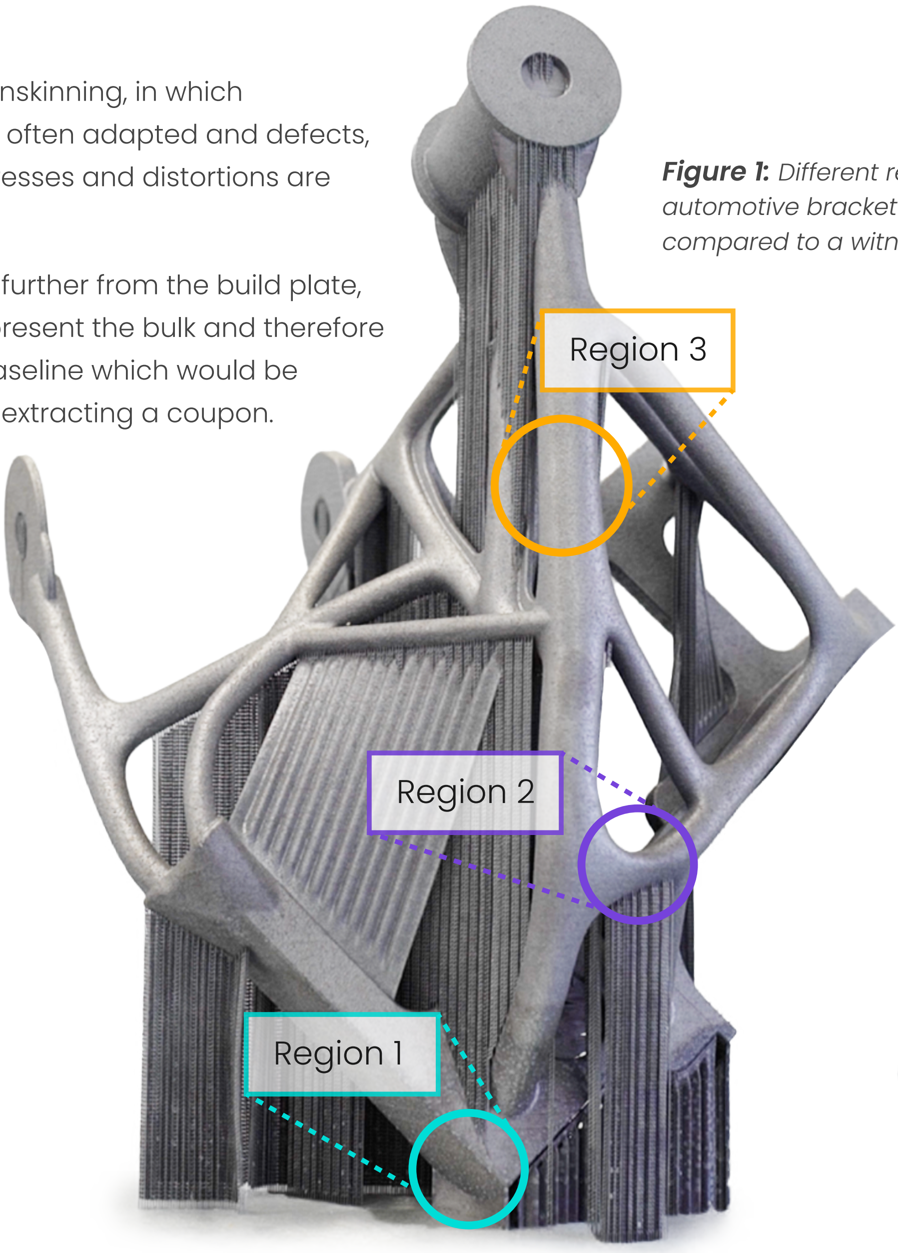
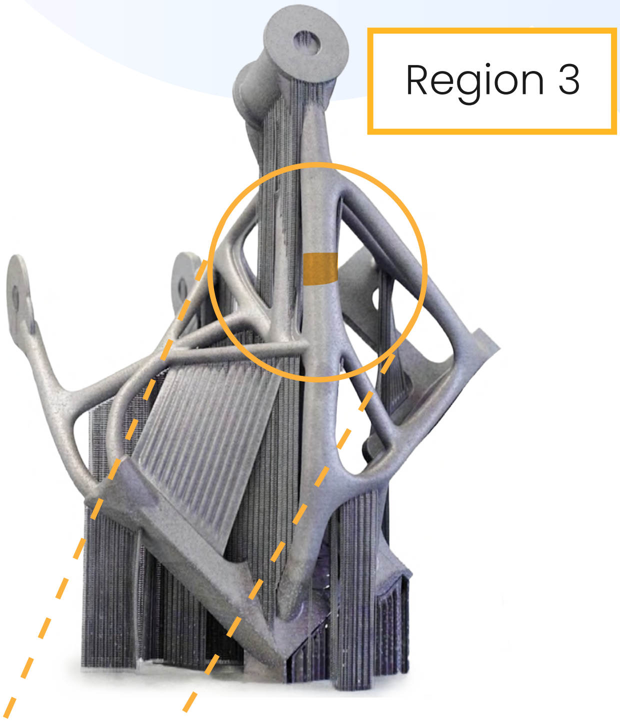


Figure 1: *Different regions of the automotive bracket were investigated and compared to a witness tensile coupon.*

Measurements

The mechanical properties (stress-strain relationships) of both the witness coupon and AM part were measured using an Indentation Plastometer, a compact indentation-based benchtop device. The technology uses the novel PIP method, developed by former University of Cambridge materials scientists at Plastometrex. PIP uses an accelerated inverse finite element method to infer accurate stress-strain curves from indentation test data.

The Indentation Plastometer comes with both 2 mm and 1 mm diameter indenter tips, allowing stress-strain measurements to be taken as close as 5 mm and 2.5 mm apart, respectively. The test itself is fully automated and takes less than 5 minutes without the need for separate coupons or extensive sample preparation. The larger diameter indenter was used in this work for testing the sample in the as-built state. Indentation was performed parallel to the build direction for the inference of stress-strain curves to produce radially symmetric indents. The part was sectioned and prepared to a 1 μm diamond finish prior to indentation in the different regions.



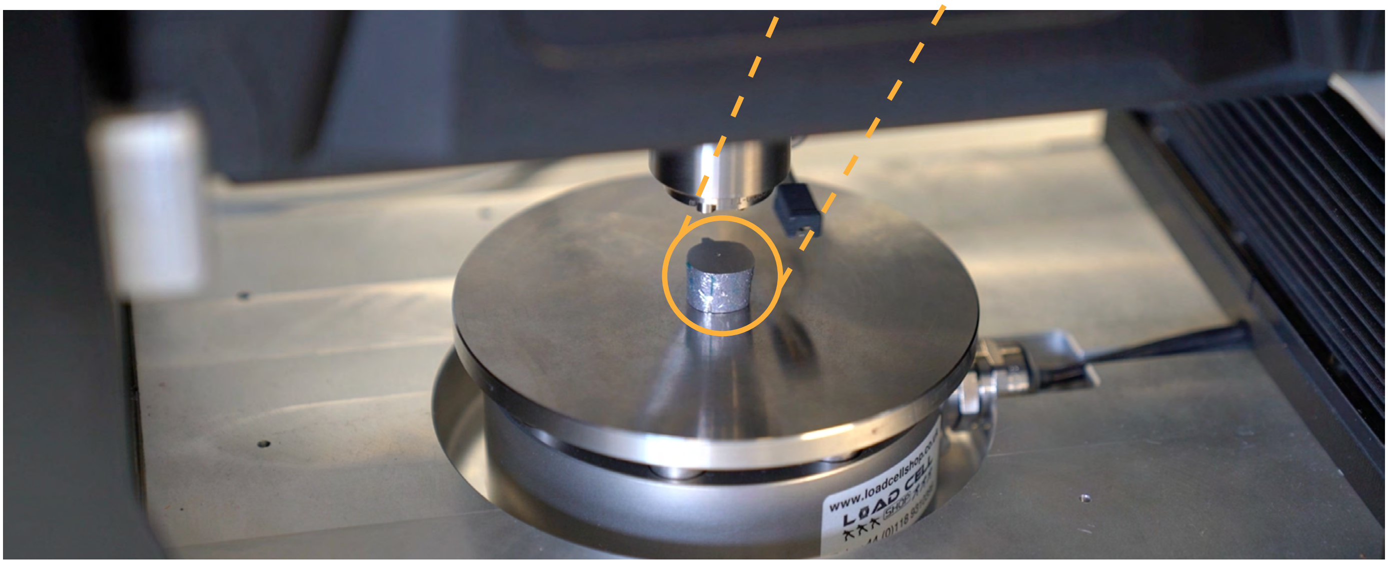


Image: *Indenting region 3 of the part with the Benchtop Plastometer.*

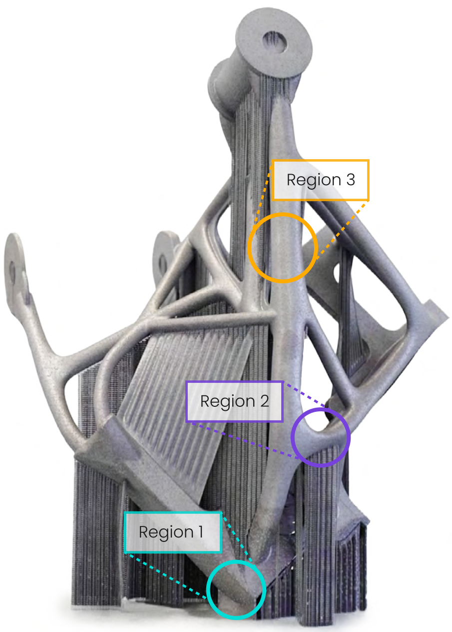
Results

In this case study we compared results from uniaxial tensile testing with those obtained from PIP tests (Figure 2) to determine whether testing on a witness coupon provides representative data of a 3D-printed part.

So, did the results from testing done on the coupon tell the same story as those done directly on the part itself? With **a variation in mechanical properties of almost 20%** in different locations, certainly not.

Region	Yield stress /MPa	UTS /MPa
Witness coupon - Tensile	250	469
Witness Coupon - PIP	277 ± 37	474 (462 - 493)
Region 1 - Near build plate	239 ± 39	476 (463 - 498)
Region 2 - Aggressive downskin	264 ± 29	415 (406 - 428)
Region 3 - Vertical Section	282 ± 34	497 (463 - 514)

Figure 2: *The witness tensile coupon was tested using uniaxial testing and PIP testing, minor differences between these results are attributed to the anisotropy confirmed to be present in the sample. PIP testing was used on different regions of the printed part.*



Results

The PIP testing performed on the printed automotive bracket in the different regions shown above yielded some interesting results. The curve from Region 2, where there was aggressive downskinning, shows a significant (>10%) reduction in UTS as compared with Regions 1 and 2. [Previous work]() by Plastometrex has indicated that distance from build plate can influence mechanical properties, however the similarity between testing in Regions 1 and 2 suggests that the part doesn't show significant inhomogeneity along the build direction, which was confirmed by testing at different build heights from the witness coupon. The lower performance of Region 2 could be due to the increased likelihood of defects in this region due to its printing conditions. The increase in effective annealing heat treatment time could provide an explanation for the lower yield of Region 1 as compared to Region 3. It is important to note that the stress-strain curves inferred from these regions, in Figure 3, will be influenced by the properties in the transverse directions as well as the build direction. These multi-directional inputs can only be obtained using a PIP test, meaning that the single-directional tensile test would show a different, less insightful, end result.

Plotting the results from the testing of the part alongside the testing of the witness coupon, as in Figure 4, shows that the mechanical behaviour in different regions of the part can differ significantly from that of the witness coupon. The witness coupon agrees well with testing in Region 3; this is attributed to the printing of Region 3 being most similar to the printing conditions of the witness coupon. The discrepancies in other regions highlight the need for testing directly on printed parts for full confidence in their mechanical properties.

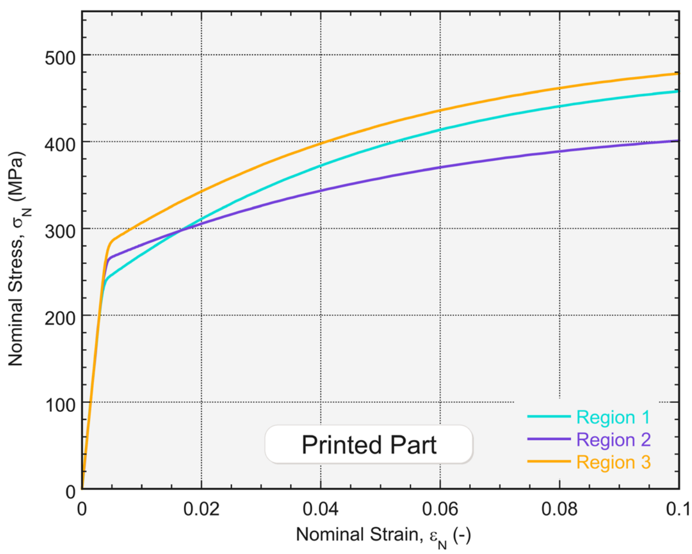


Figure 3: *PIP testing shows that different regions of the part show different mechanical behaviour.*

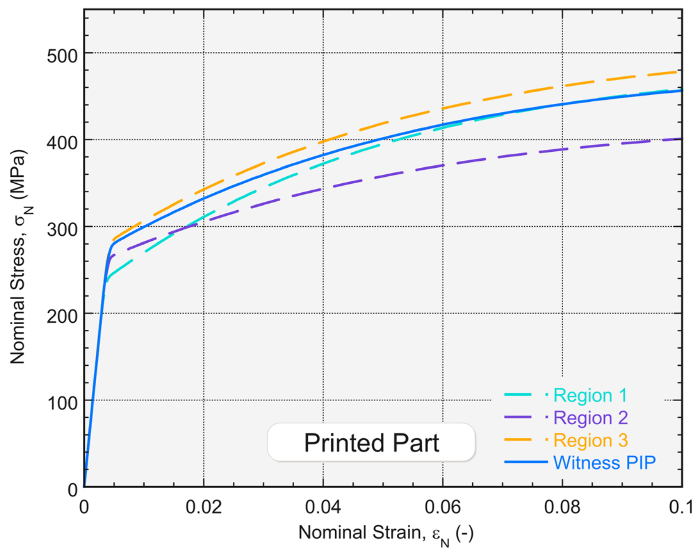


Figure 4: *PIP testing on the witness coupon shows differences in behaviour between the witness coupon and the part itself.*

Outcomes

As demonstrated, current reliance on witness coupons to test the mechanical properties of a 3D-printed part may not accurately represent the whole component, as the mechanical behaviour in different regions of the part can differ significantly from that of the witness coupon. As a result, relying on data obtained from witness coupons can result in additively manufactured parts literally "cracking under pressure" in industries such as automotive, defense, and aerospace, where failure can be nothing short of catastrophic.

The ability of the PIP testing method to characterise additively manufactured parts directly and in multiple locations on an AM part is invaluable for both the modelling of these components and ensuring full confidence in their strengths across different regions. Not only is PIP testing >90% faster and cheaper than traditional mechanical testing methods for AM, it provides a much more accurate representation of the mechanical properties of the printed part. This, in turn, allows for more informed design strategies that can produce the desired properties in different regions of parts, ultimately leading to increased efficiency and cost savings in the additive manufacturing process, and, most importantly, parts that users can rely on to perform.

Find out more about PIP Testing for AM

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