



PLASTOMETREX



CASE STUDY

Baked to Perfection:

Renishaw's Insights Into AM Heat Treatment Sensitivity Using PIP

In collaboration with

RENISHAW 

A large, black industrial 3D printer with the Renishaw logo and 'RenAM 500Q Ultra' text in orange and white. A control panel with a screen is visible on the right side.

RENISHAW

RenAM 500Q Ultra

Challenge

Heat treatment is a common step in the additive manufacturing (AM) process, used by engineers to control the performance and properties of additively manufactured parts. It's often a crucial part of turning these intricate designs into strong, usable components that can stand up to the demands of its intended operating environment. We rely on this process to make sure that part properties are optimised for their application, ensuring high performance and longevity in service.

But what if this process, designed to enhance and strengthen, could in fact leave us open to local property variations? In this case study with Renishaw, we uncover how the varying temperatures throughout a furnace have a significant impact on the mechanical properties of AM parts, in this case showing over 10% variation in yield strength, and how these findings have led Renishaw to optimise their heat treatment process, ensuring consistency and increasing confidence in part performance.

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Objectives

This case study aims to highlight the variation in mechanical properties across a set of builds which can arise during heat treatments of AM parts and how these variations can be characterised quickly and effectively.

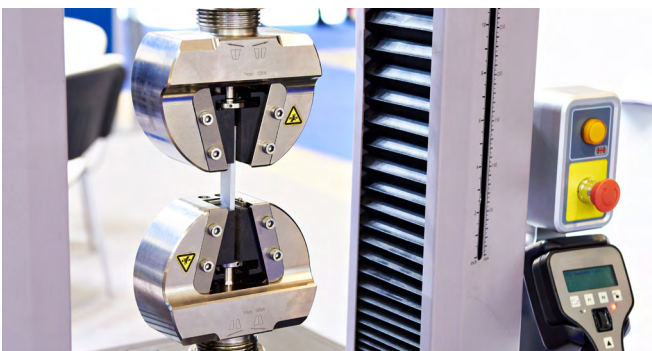
AM materials are commonly heat treated to optimise the properties of the parts and maximise their performance. However, non-uniform heating and cooling conditions within a furnace, due to variable gas flows and heater positioning, can generate unknown variations in heating conditions and resulting mechanical properties. This can increase part-to-part variation or result in differential properties across a large build. Furnace temperature variation can be mapped using thermocouple arrays; however, this does not capture the temperature across the whole build or any direct information about the resulting effect on the material properties.

Another option for verifying and characterising this variation in heat treatment conditions could be to tensile test a large number of witness coupons from across the part (although there is no guarantee that a witness coupon will have experienced a uniform heat treatment across

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the entire gauge length). Again, this option is not just time, but also material and cost intensive. Hardness testing could generate mechanical data on a finer scale, however these tests generate far less information than a full stress-strain curve does.

This case study will show how valuable insight into the inhomogeneity associated with rapid cooling heat treatment, can be obtained using Profilometry-based Indentation Plastometry (PIP) due to the technique's fine spatial resolution, allowing for accurate mapping of variations in mechanical properties, whilst accelerating testing times and reducing the substantial material requirements associated with pulling witness coupons.



To use tensile testing to characterise variation in heat treatment conditions would require high volumes of material and time, without a guarantee of a tensile coupon having experienced a uniform heat treatment across the entire gauge length.



PIP testing allows for accurate mapping of variations in mechanical properties, whilst accelerating testing times and reducing material requirements substantially.

Materials

Two Inconel 718 builds, each consisting of 16 tensile coupons were built by Renishaw for this work, using laser powder bed fusion. The tensile coupons were all printed vertically, such that the probed tensile direction was parallel to the build direction. Both builds were then heat treated by Renishaw, together in the same vacuum furnace, using their standard [Inconel 718 heat treatment](#). A 1 bar argon gas quench was used after the solutioning and ageing stages, with the gas inlet positioned at the front of the furnace.

16 of the 32 coupons were positioned at the back of the furnace, ~280 mm from the argon

inlet, whilst the other 16 were positioned at the front of the furnace, as close as 15 mm from the argon inlet (Figure 1). Having been heat treated, the coupons were tested in uniaxial tension and PIP tests were subsequently carried out on the threaded tensile ends. This allowed any variability in the mechanical properties to be characterised through both the tensile and PIP results.

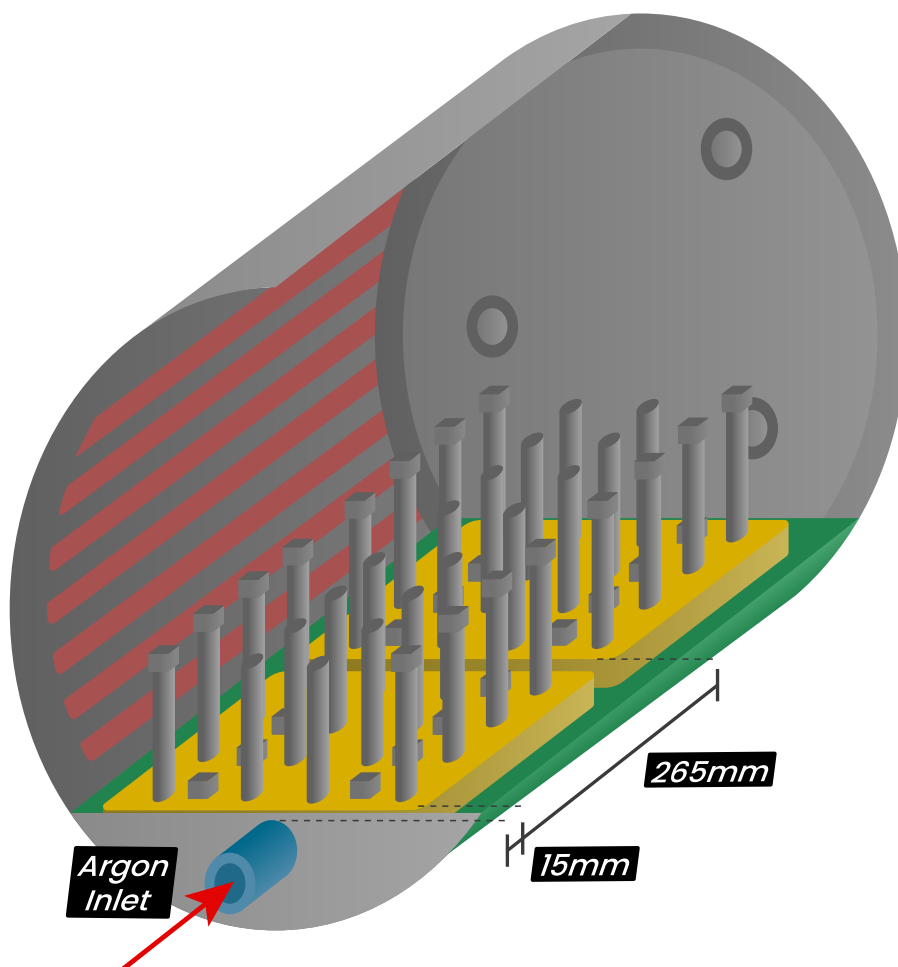


Figure 1: Diagram of a vacuum furnace with 16 coupons placed near the back, about 280 mm from the argon inlet, and 16 coupons positioned about 15 mm from the argon inlet at the front of the furnace.

Measurements

The mechanical properties of the Inconel 718 samples were determined using conventional tensile testing and PIP testing.

PIP is an indentation-based technique which can rapidly derive the stress-strain curve of metallic materials. An indent, approximately 1 mm in diameter and 150 µm in depth, is generated using a spherical indenter tip and the residual indent shape is then characterised using a contacting stylus profilometer. Using the indent shape and an integrated inverse finite element simulation method, accurate stress-strain curves can be inferred from the indent. The test process is fully automated using a [PLX-Benchtop](#) device and the full test takes only around 5 minutes to complete.

The PIP tests were carried out directly on six of the threaded tensile ends such that the indentation direction was parallel to the build direction. A basic surface preparation to a mirror finish was applied to the indented surfaces prior to PIP testing.



[PLX-Benchtop](#) by Plastometrex.

Results

The trends identified from the PIP results provided significant insight for Renishaw about the sensitivity of mechanical properties on the variable temperatures generated within the same heat treatment run.

The PIP-derived stress-strain curves for the samples at the front and back of the furnace, shown in Figure 2, were compared to unlock this insight. The position within the furnace had minimal

effect on the measured UTS values, but a more significant effect on the yield stress: the average PIP-derived yield stresses, shown in Table 1, were ~140 MPa (11%) lower for the samples at the front of the furnace compared with the back.



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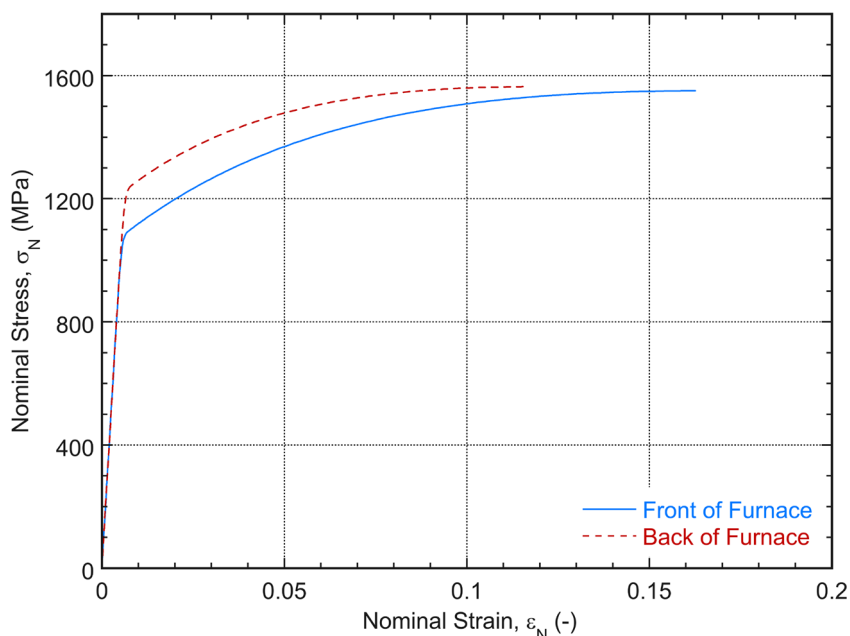


Figure 2: Representative PIP-derived nominal stress-strain curves from each heat treated Inconel 718 build, situated either at the front or back of the furnace at Renishaw.

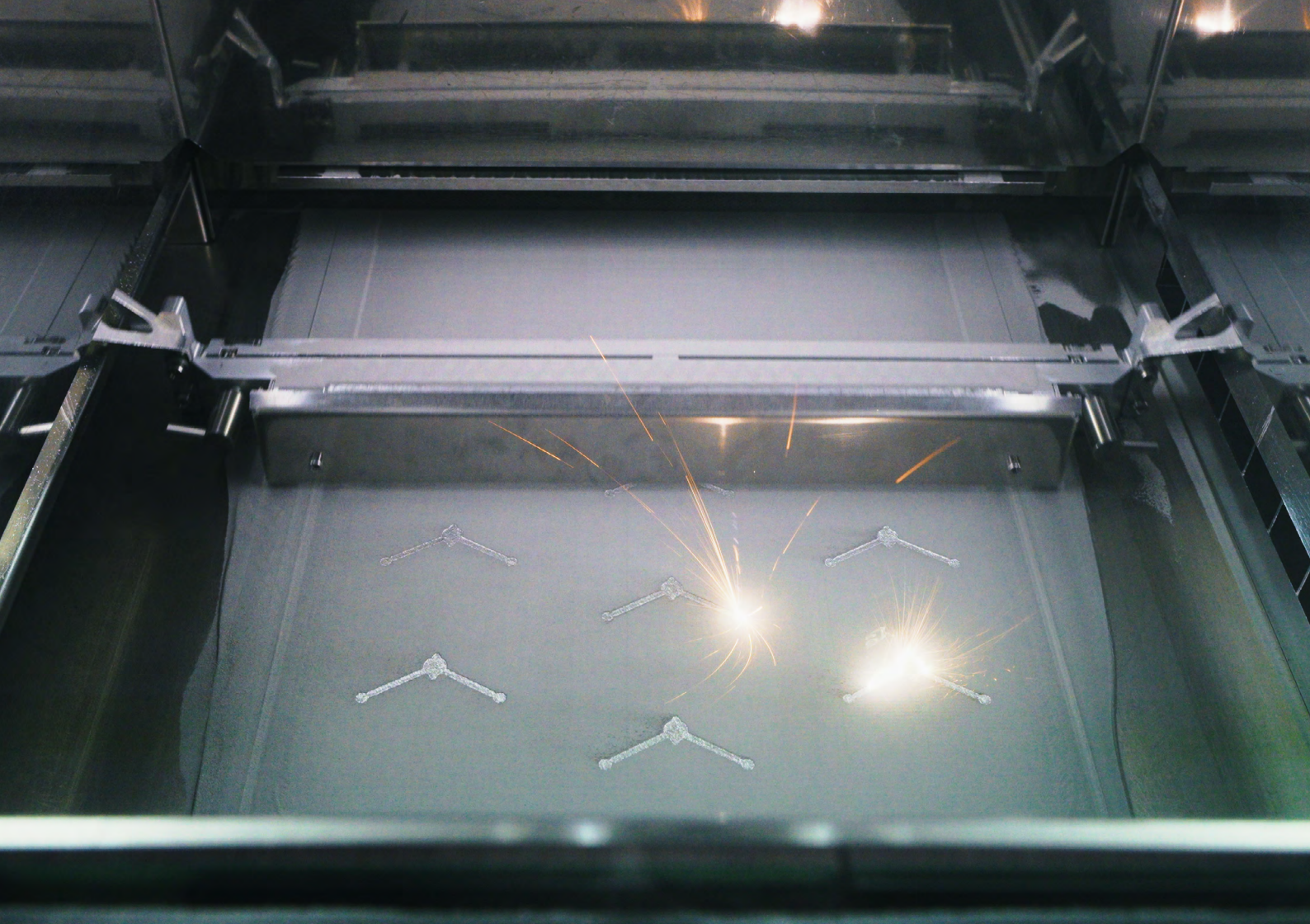
	Front of Furnace	Back of Furnace
Average Yield Stress / MPa	1068	1205
Average UTS / MPa	1554	1574

Table 1: Averaged PIP-derived yield stress and UTS values, for Inconel 718 heat treated at the front and back of the furnace at Renishaw.

The tensile stress-strain curves also exhibited similar trends, with a reduction in yield stress for samples at the front of the furnace and insignificant differences between measured ultimate tensile strengths, whilst also showing good agreement with the PIP-derived results. However, identifying this trend using PIP is a much faster process, with no significant machining requirements. In fact, PIP can be carried out on a printed and heat-treated

part with only a small amount of preparation. This allows the effects of the heat treatment across a part to be mapped at a far finer resolution compared with tensile testing using a separate coupon, providing invaluable insight into the efficacy of heat treatments across a large or complex part. Through PIP testing, this understanding can be achieved with significantly less demand on time and printed material.





Outcomes

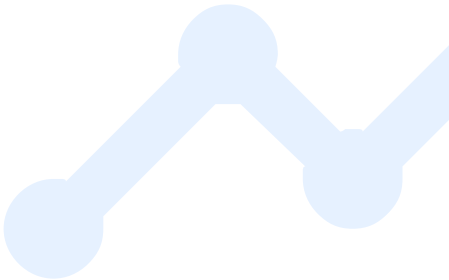
Where gas quenching is used, the location of a part inside the heat treatment furnace can significantly affect its mechanical properties, including its yield strength. Our findings show that parts placed at the front of the furnace (closer to the argon inlet) have an 11% lower yield stress compared with those at the back. This study has enabled Renishaw to identify variation in gas flow conditions when multiple builds are in the furnace, allowing for the implementation of heat treatment best practices to ensure consistency across builds.

Through this discovery and the use of PIP testing, Renishaw is now able to get a fuller picture of the integrity of parts post-heat treatment than hardness testing alone can provide, without incurring the time and cost

penalties associated with tensile testing. For Renishaw printing and testing this Inconel 718 material, the cost for a PIP test is around half that of a conventional tensile test and a quarter of the sample preparation time. PIP-derived results equip Renishaw with valuable insights for enhancing heat treatment process developments and understanding their impact. PIP also offers a means to gather actionable information about mechanical properties quickly and easily without needing large volumes of material. At Renishaw, the findings presented in this case study were used to

inform the decision to limit the number of builds or built parts from being simultaneously heat treated in the same furnace, preventing any variation in mechanical properties from being introduced due to furnace position.

Performing PIP studies on small witness coupons also offers potential benefits during production and could be used as a fast and inexpensive way to validate part performance with high spatial resolution. Using PIP as part of a quality assurance process can demonstrate compliance with minimum performance thresholds, measure property variation and provide confidence in results to internal stakeholders, customers and regulatory bodies.



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Conclusion

This case study, in collaboration with Renishaw, has been able to demonstrate the value PIP can deliver in rapidly identifying heat treatment associated property variation for a significantly reduced cost compared with traditional tensile testing. Renishaw were able to identify inconsistent conditions during heat treatment and exposed how the position within the furnace resulted in significant variations in mechanical properties. This variable cooling during heat treatment of AM samples can

result in significant variation in part properties. Whilst uniaxial testing of witness coupons can provide some insight to furnace conditions and the effect on mechanical properties, PIP is faster and less costly, as well as offering an advantage in providing finer scale resolution for mapping properties over builds. This provides Renishaw with a competitive advantage in characterising their AM parts, as well as requiring significantly less material for testing, saving time and cost for printing.

See the technology in action...

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Learn more about the PLX-Benchtop with one of our informal virtual technology demonstrations. Presented by our friendly team of material scientists, you'll hear a bit more about our work here at Plastometrex before seeing the plastometer conduct a live test. Feel free to invite your colleagues along, too!

