The impact of TEMPUS™ technology

Executive summary

This white paper describes the impact of TEMPUS™ technology, a new capability for the RenAM 500 series of metal additive manufacturing (AM) systems.

TEMPUS technology enables the system lasers to fire while the recoater is moving, reducing layer duration and increasing productivity by up to 138%.

A comparative study of conventional and TEMPUS processing methods has shown that both approaches achieve equivalent material properties after heat treatment for four different alloys.

The study also evaluated the impact of TEMPUS technology on surface roughness, volumetric density, and geometric accuracy, and found no significant difference between parts built with or without TEMPUS technology.

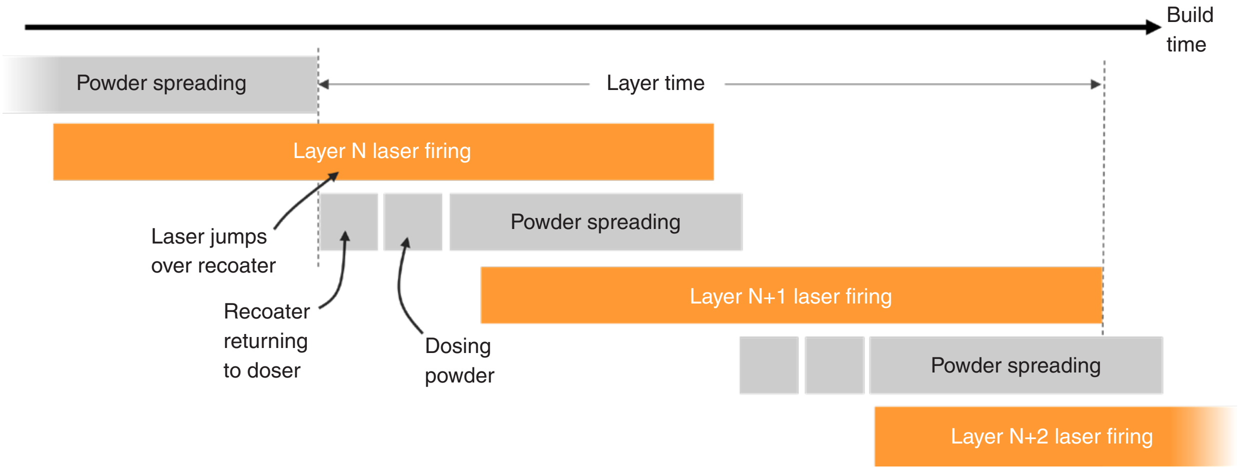


Figure 1 TEMPUS technology layer sequence

1. Introduction

Part cost remains the biggest barrier to additive manufacturing (AM) adoption, and the biggest contributor to this cost is time spent building on the AM machine. Any decrease in build time can significantly lower the cost embodied in the parts they produce.

Traditionally, laser powder bed fusion (LPBF) machines turn the laser(s) off while powder is being dosed and spread, as well as while the recoater returns to the doser. Preparing the powder layer takes approximately ten seconds. With builds regularly consisting of thousands of layers, this accumulated recoating time can contribute a significant portion of the build time (see Table 1).

Number of layers	Time spent preparing the powder layer traditionally (approximate) [hours]
1000	2.75
2000	5.5
3000	8.25
4000	11
5000	13.75

Table 1: Total powder recoating time for traditional LPBF systems

TEMPUS™ technology, a new capability for the RenAM 500 series of metal AM systems, can eliminate the build time contribution of this recoating time. By enabling the system lasers to fire while the recoater is moving, it is possible to double productivity, reduce build time by up to 50% and significantly reduce part costs.

This document provides a detailed breakdown of the technical processes performed by TEMPUS technology, its productivity impact, and the detailed material testing Renishaw undertook to evaluate whether TEMPUS technology affects part quality. Frequently asked questions for RenAM 500 series users are also answered in Appendix A.

1.1 How TEMPUS technology works

TEMPUS technology consists of the following components:

- Hardware control systems integrated into the optical, recoater and Z-axis subsystems.
- On-machine software controller, co-ordinating activity across all subsystems.
- The **.renam** file format, which contains deterministic (time-controlled) instructions for the optical, recoater and Z-axis subsystems.
- QuantAM build preparation software, encoding sub-system behaviour into the **.renam** file format.

This combination of hardware, controller, and software capability enables advanced control of laser positioning and timing, and co-ordination with the recoater and Z-axis. This enables the laser(s) to continue firing as the recoater adds a new layer of powder.

Figure 2 shows how the recoater and lasers interact throughout the build with TEMPUS technology enabled.

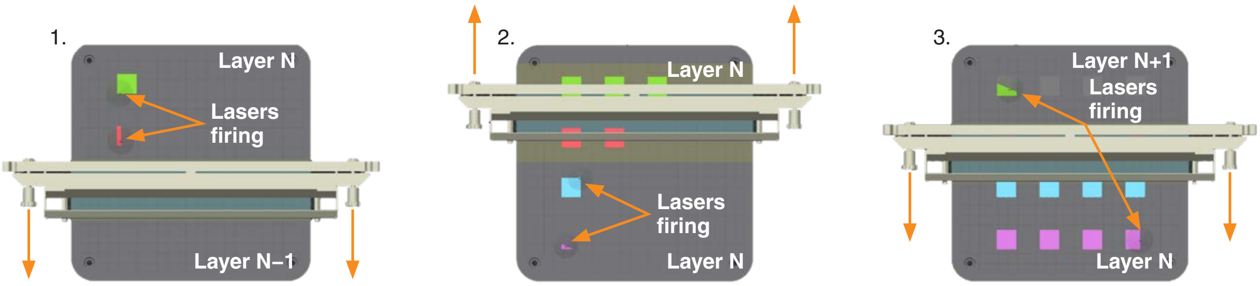


Figure 2 TEMPUS technology recoating process over two layers

1. As the recoater spreads a layer of powder, the lasers ‘follow’ the recoater, melting the powder being spread before the recoater completes its stroke.
2. When the recoater returns to doser to collect more powder, the lasers ‘jump over’ the recoater and continue melting the current layer. The Z-axis elevator will dip lower to prevent the recoater interacting with the powder on return to the doser – the active laser(s) focal length is dynamically adjusted to keep the powder plane in focus. The Z-axis then returns to the appropriate position for spreading powder on layer N+1.
3. As the recoater begins spreading the next layer of powder, the lasers finish the previous layer, and start processing the new layer, simultaneously.

The result of this capability is a significantly shortened layer duration. Compared with the sequential process typical of LPBF systems (see Figure 3 below), the layer sequence with TEMPUS technology includes simultaneous powder recoating and laser firing actions (see Figure 4). The TEMPUS technology sequence reduces build time every layer which, accumulated over the entire build, can significantly reduce total build duration.

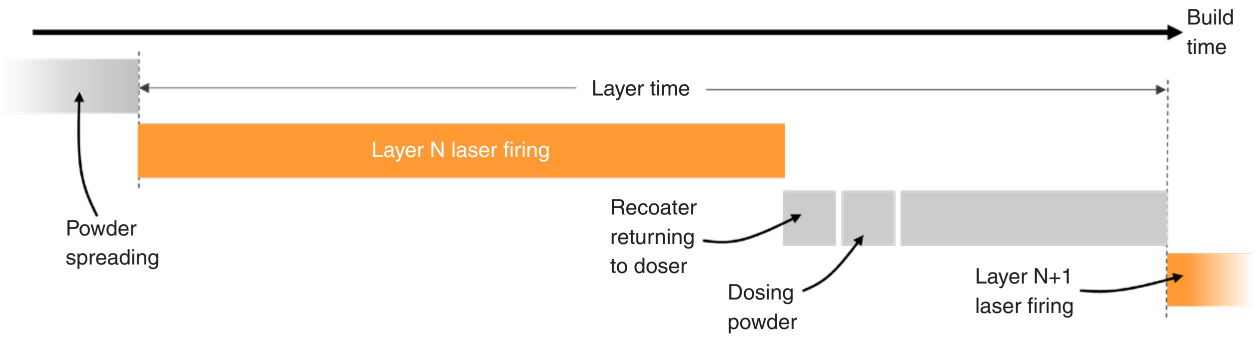


Figure 3 Traditional LPBF layer sequence

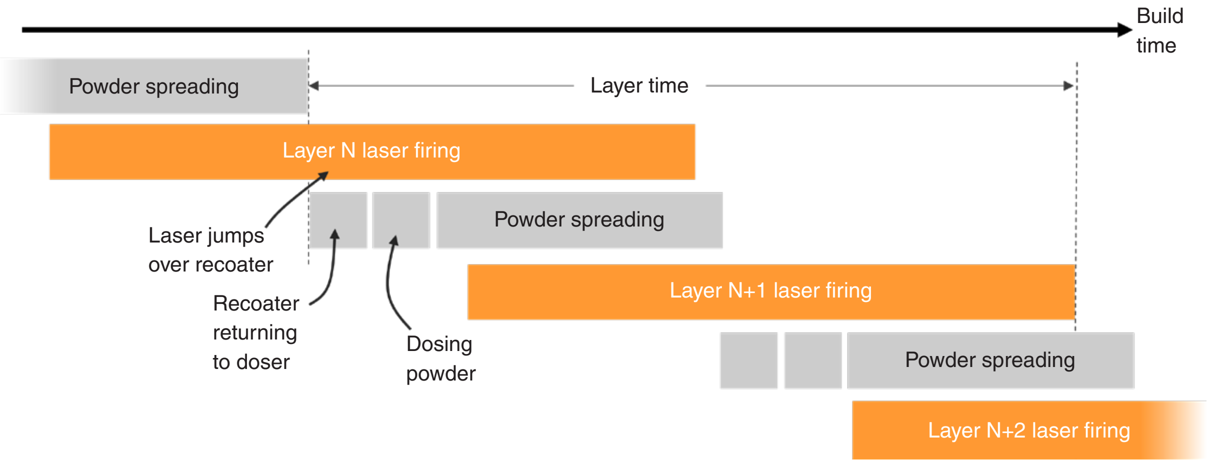


Figure 4 TEMPUS technology layer sequence

2. Impact of TEMPUS technology on productivity

Two factors contribute to the build time saving possible with TEMPUS technology:

- Reduction in the time the recoater takes to prepare a powder layer from 9 seconds to 6.5 seconds.
- Ability to fire the laser(s) while the recoater is preparing the powder layer (up to 6.5 seconds saved).

The reduction in recoating time is possible due to the integration of recoater and Z-axis subsystems with the optical controller. Typically, these subsystems act independently and programmed delays are used to ensure the recoater and Z-axis actions have fully completed before any laser firing takes place. With the advanced system controller co-ordinating the activities for all of these subsystems, based on a deterministic renam build file, these programmed delays are no longer necessary. These delays equate to approximately 2.5 seconds per layer which can be saved. Even if the laser is not fired while the recoater is spreading powder, the layer duration can be reduced to approximately 6.5 seconds (down from 9 seconds).

As described in Section 1.1, TEMPUS technology enables the laser(s) to fire during the 6.5 second recoating process. In a theoretical, fully optimised scenario, the entire recoating duration could be used for laser firing, resulting in a 9 second per layer time saving versus a conventional LPBF process. With differing total durations of laser firing, the 9 second saving will represent a different proportional saving. As shown in Table 2, which shows four example scenarios (A, B, C, D), the greatest proportional saving possible is achieved when the laser firing duration is 6.5 seconds, equal to the TEMPUS recoating time. A 58% reduction in layer duration is the equivalent of a 138% increase in productivity (i.e. productivity is more than doubled).

	Traditional LPBF layer timing [seconds]			**TEMPUS technology layer timing [seconds]**			**Saving**	
	Recoating	**Laser(s) firing**	**Total layer**	**Recoating**	**Laser(s) firing**	**Total layer** [1]	**Time [seconds]**	**%**
A	9	1	10	6.5	1	6.5	3.5	35%
B	9	6.5	15.5	6.5	6.5	6.5	9	58%
C	9	9	18	6.5	9	9	9	50%
D	9	20	29	6.5	20	20	9	45%

[1] Theoretical optimised layer duration achievable – see Figure 4 for impact of file optimisation on TEMPUS technology layer duration and time saving.

Table 2: Example layer durations with and without TEMPUS technology

In practice, there are competing factors when optimising an AM build, including part nesting, laser assignment and optimisation for gas flow. Depending on the combination of these factors, and the part geometry, it is not always suitable to optimise exclusively for productivity. Figure 5 illustrates how the proportional time saving is affected by variation in how much of the recoating time is used for firing the lasers. If 0% of the recoating time is used for firing the lasers, the only time saving from a traditional LPBF process is due to the 2.5 seconds of eliminated system delays.

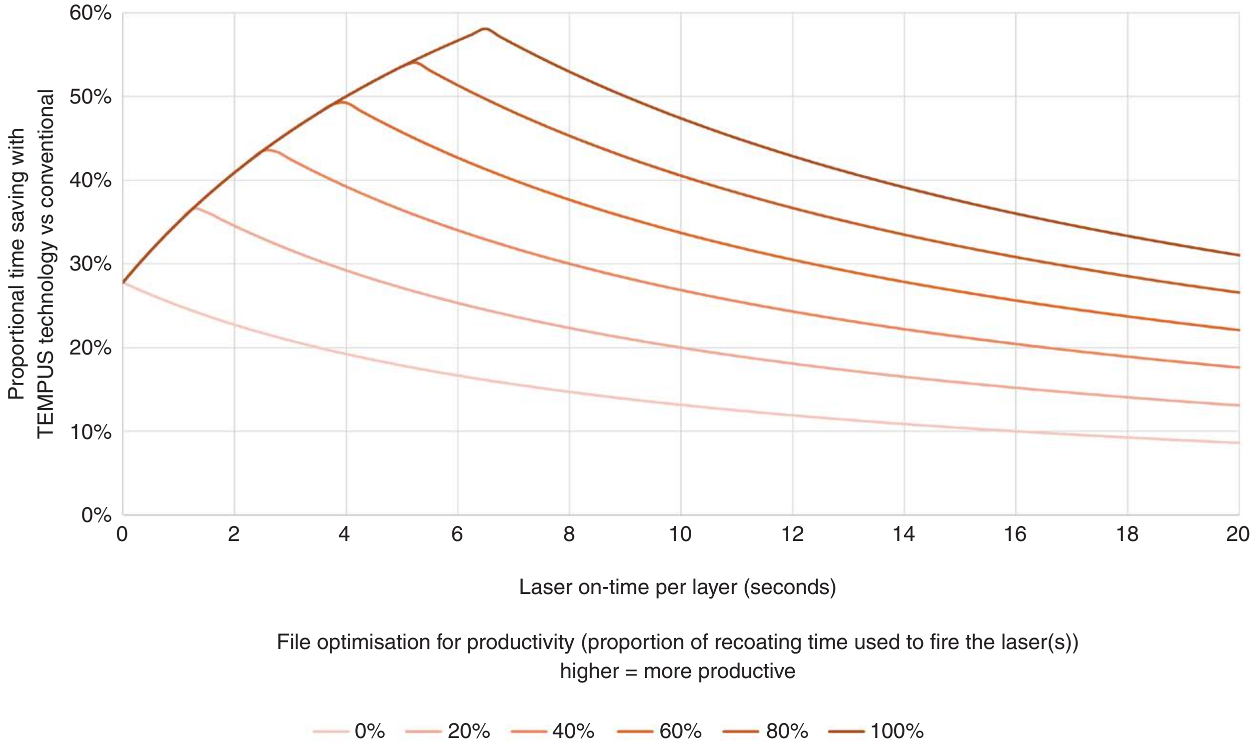


Figure 5 Impact of build file optimisation on TEMPUS technology productivity gain

Another practical element relevant to the impact of TEMPUS technology on productivity is shift patterns. Availability of an operator to remove a build from the AM machine and prepare the system for the next build can be the bottleneck for volume production. In some applications, the build time saving achieved with TEMPUS technology enables multiple builds to be completed within a single shift where previously only one was possible. This can result in a greater proportional increase in system throughput than the time saving would indicate. For example, a 25% build time saving which enabled a second build to be started at the end of a day shift could double the system build capacity.

Visit **www.renishaw.com/tempus** to see case studies across a range of applications. In all cases, TEMPUS technology enables a productivity boost, reduced build time and so reduces cost per part.

3. Impact of TEMPUS technology on part quality

3.1 Introduction to the testing

Higher quality metal delivers better mechanical properties, which enables the same in-life performance with less material, and thinner and lighter designs. Lower mass means faster printing – so it is only by increasing the build rate (with TEMPUS technology), and maintaining process quality, that it's possible to maximise productivity.

To quantify the impact of TEMPUS technology on part quality, the following part properties were evaluated for four different materials:

- 3.3 Mechanical properties:
  - Elongation
  - Yield strength
  - Ultimate Tensile Strength (UTS)
- 3.5 Hardness
- 3.6 Surface roughness
- 3.4 Volumetric density
- 3.7 Geometric accuracy

3.2 Hypothesis

There are three mechanisms by which TEMPUS technology could impact part quality:

1. Faster processing of the build results in altered as-built [2] microstructure and therefore part properties (applicable to any productivity technology).
2. Faster processing of the build results in elevated powder bed temperatures, causing semi-sintering of the powder.
3. Firing the laser while the recoater and Z-axis move disrupts melting conditions (including gas flow), resulting in part defects or geometric inaccuracy (specific to TEMPUS technology).

[2] As opposed to heat treated.

3.2.1 Microstructure

Processing a build more quickly will change the thermal dynamics of the system. Introducing the same laser energy (dictated by the build file parameters) over a shorter period will result in greater heating. Each layer has less time to cool before the subsequent layer is processed. Figure 6 shows how heat is conducted from the weld track into the solidified material in previous layers.

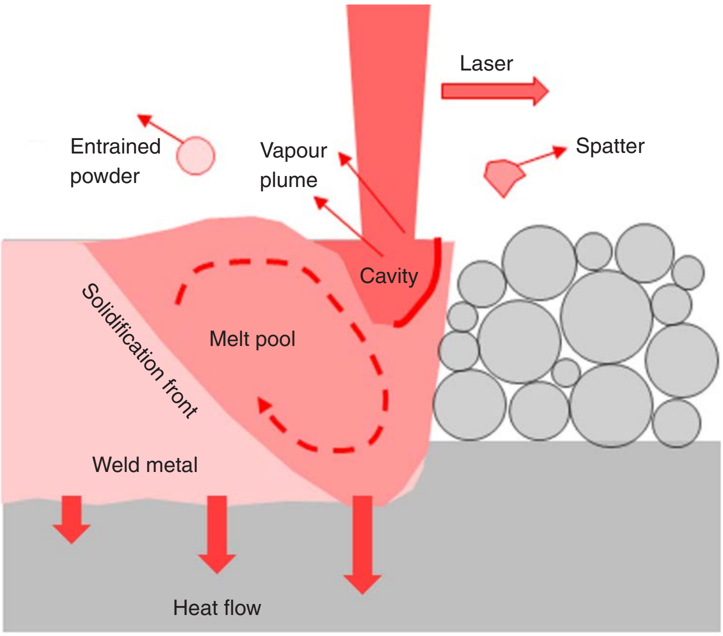
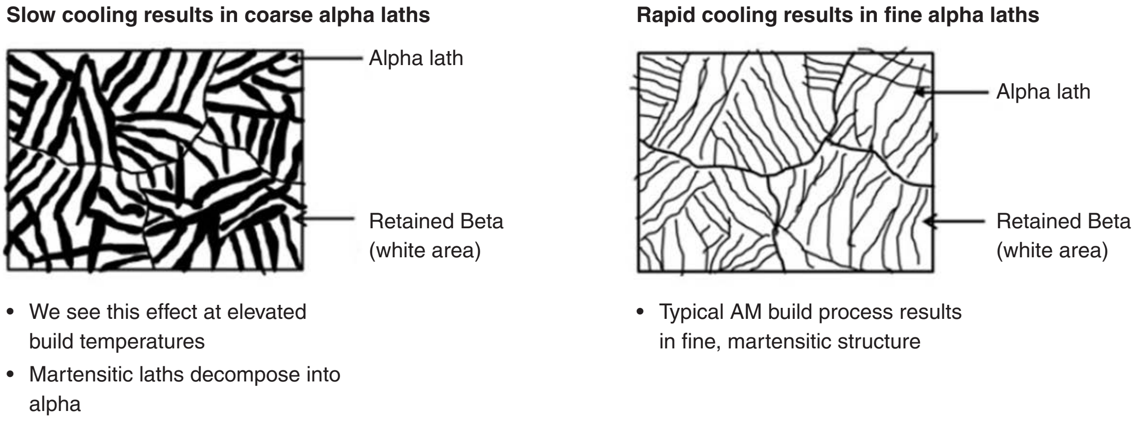


Figure 6 Heat flows during laser powder bed fusion

Source: Adapted from Spatter matters! LinkedIn article by Marc Saunders

The effects of a higher substrate temperature (typically achieved using a heated bed) is understood to reduce the cooling rate of subsequent layers (due to a lower temperature differential). The lower thermal gradient (i.e. slower cooling rate) experienced by the melt track can impact the as-built microstructure as well as reduce residual stress [3].

As shown in Figure 7, for Ti6Al4V titanium alloy slower cooling would be expected to result in coarser alpha lath formation and a reduced martensitic microstructure.



- We see this effect at elevated build temperatures
- Martensitic laths decompose into alpha

- Typical AM build process results in fine, martensitic structure

Figure 7 Impact of cooling rates on microstructure in Ti6Al4V

Source: Want to build AM parts? No Stress! LinkedIn article by Marc Saunders, Renishaw

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[3] Thermally activated atomic diffusion increases, relieving internal strain energy.

As a result, it is expected that Ti6Al4V produced using TEMPUS technology will demonstrate a lower ultimate tensile strength (UTS), higher elongation and decreased hardness in the as-built state; fewer grain boundaries provide less hindrance to dislocation and deformation. The impact on as-built microstructure and mechanical properties due to increased processing temperatures will vary by material. The degree to which the microstructure will be affected is also geometry dependent; as outlined in Section 2, the amount of recoating time that can be utilised when considering all factors (such as part nesting, gas flow etc) will significantly impact how much additional heat is present during laser melting.

For the vast majority of applications, it is standard practice to heat treat AM parts to achieve the required microstructure and associated mechanical properties. It is hypothesised that any difference in as-built microstructure when processing with TEMPUS technology can be eliminated through heat treatment. As such, the mechanical properties for parts built using TEMPUS technology and heat treated are expected to be equivalent to conventional AM parts.

3.2.2 Semi-sintering

Elevated powder temperatures due to faster processing will be concentrated adjacent to the melt track. Therefore, any semi-sintering would be expected to occur on the surfaces of solidified parts. Therefore, if this effect is present, it would exhibit as increased surface roughness. As with the microstructure, the degree to which this effect will occur is material and geometry dependent. As discussed in Section 2, if the maximum recoating time can be utilised, the increased productivity and reduced layer times will result in additional heat and is more likely to impact surface roughness.

In the same way that, for applications with critical mechanical properties, heat treatment can be used to achieve the required microstructure, surface roughness can be modified after building. Post-processing techniques including grit blasting and machining are commonly used to alter the as-built surface finish to meet application requirements.

It is hypothesised that the increase in powder temperature related to TEMPUS technology could result in increased surface roughness depending on the material and geometry. It is expected that any difference in as-built surface finish could be eliminated through subsequent post-processing.

3.2.3 Part defects

TEMPUS technology modifies the melting conditions in that both the recoater and Z-axis are able to move during laser melting.

The maximum distance that the Z-axis elevator can be programmed to ‘dip’ during the build process is 2 mm (typical values are 0.2 mm to 0.3 mm). This occurs as the recoater begins its return to the doser to prevent the recoater interacting with the powder layer. The Z-axis then returns to the required height for the next powder layer to be spread by the time powder has been dosed. This dynamic change in the powder plane during the layer is compensated for through adjustment of the laser focal length and beam angle to keep the spot focused in the correct XY position. The Rayleigh length [4] of the laser on the RenAM 500 is approximately 4.5 mm, meaning that even without compensation, variation of beam length of < 2 mm would not result in a significant change in laser spot intensity (see Figure 8).

[4] The Rayleigh length is the distance along the propagation direction of the beam from the waist to the place where the area of the cross-section is doubled (i.e. where the energy density is half).

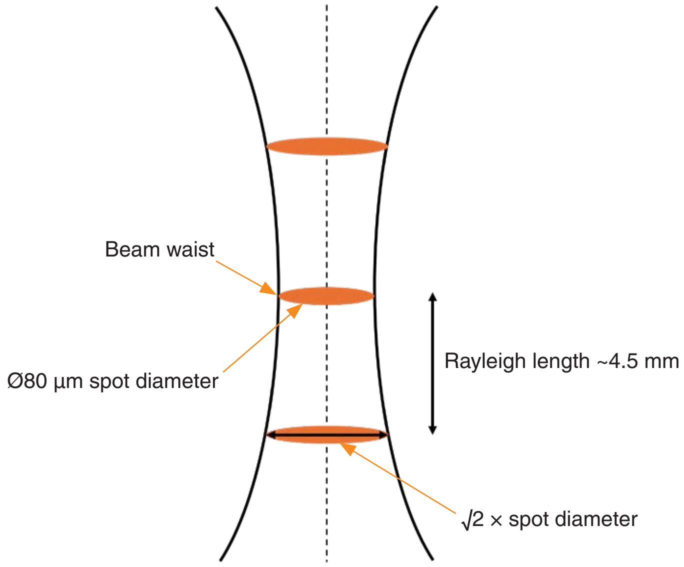


Figure 8 Beam waist and Rayleigh length

The impact of focus variation on part quality can also be confirmed experimentally, Figure 9 shows variation in bulk density for SS316L cube samples built with varying focus offset values. This data confirms that for small variations in focus offset, there is no significant impact of part quality.

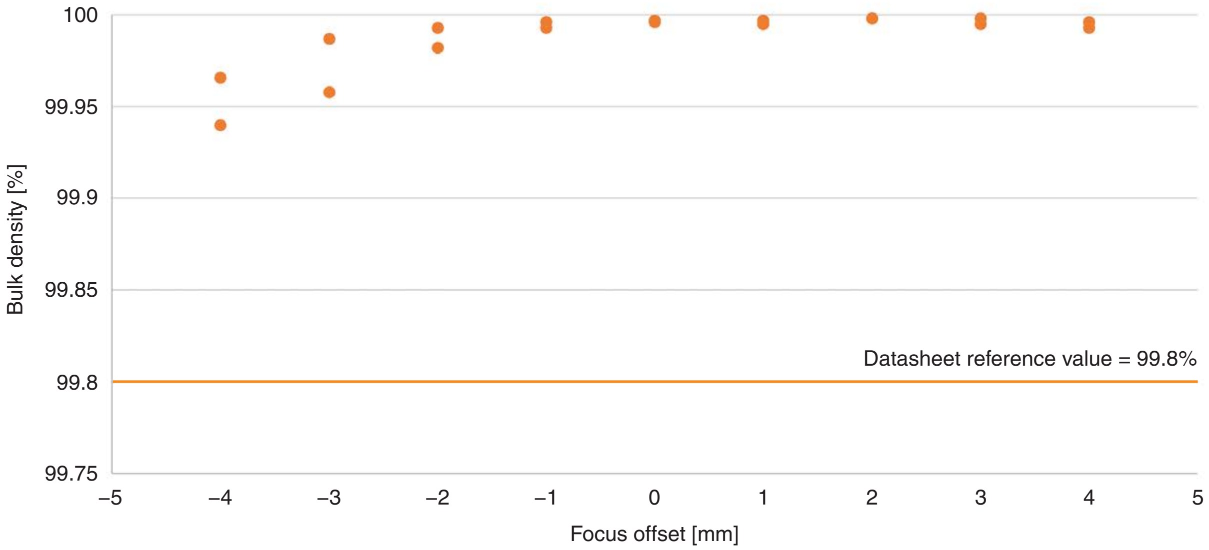


Figure 9 Variation of bulk density with focus offset for SS316L

The compensation in focal length and XY position uses the same control algorithms that are needed to keep the laser in focus and correctly positioned during normal operation. Given the presence of a Renishaw RESOLUTE™ optical encoder on the Z-axis (with 1 nm resolution), and laser Rayleigh length, it is hypothesised that the dynamic Z-axis movement will not result in any change in part accuracy.

With TEMPUS technology, the recoater can move through the gas flow above the powder bed during laser melting. It is understood that the gas flow is critical for carrying airborne material (spatter and condensate) away from the melt pool to prevent obscuring or diffracting the laser beam (see Figure 10). If TEMPUS technology disrupts the gas flow we would expect to see increased spatter and condensate interactions with the laser, resulting in lack of fusion defects and increased porosity. This would exhibit as reduced mechanical properties and reduced density.

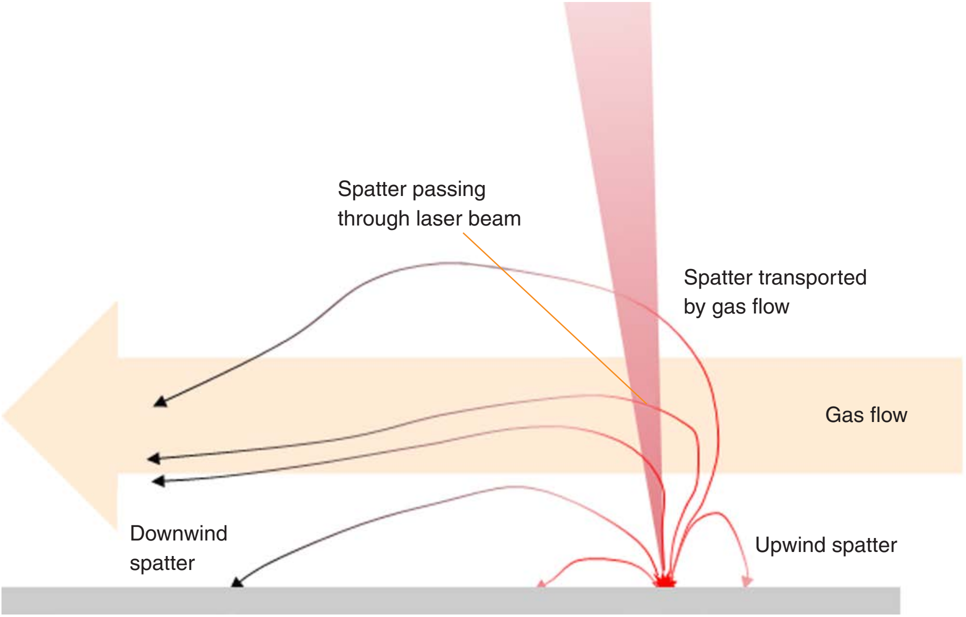


Figure 10 Role of gas flow in transporting spatter away from the melt pool

Source: Spatter Matters! LinkedIn article by Marc Saunders, Renishaw

To ensure there are no unintended interactions between the laser and recoater, there is a programmable exclusion zone around the recoater where the laser will not fire. Therefore, it is hypothesised that there will not be a significant disruption to the gas flow in proximity to the melt pool, and so density and material properties will be unaffected.

3.3 Mechanical properties

3.3.1 Method

3.3.1.1 AM build set-up

The following four alloys were tested, representing a range of material types:

Material	Material build parameter file used
Ti6Al4V titanium	Ti6Al4V_500QS_B60_S_01_A.xml
Co28Cr6Mo cobalt chrome	CoCr_500QS_B60_S_01_A.xml
SS316L stainless steel	SS316L_500QS_B60_S_01_A.xml
Inconel 718 nickel superalloy	In718_500QS_B60_S_01_A.xml

Table 3: Materials tested and parameters used

32 tensile bar blanks were arrayed vertically onto a build to cover the entire working volume as shown in Figure 11. A hexagonal density and hardness test artefact was built into the base of each tensile bar. The four system lasers were assigned as per Figure 12 to minimise any interaction between laser smoke plumes and downwind melting.

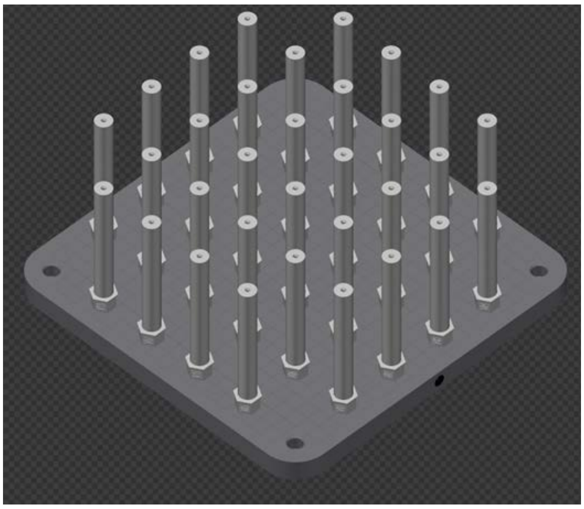


Figure 11 Mechanical property build layout

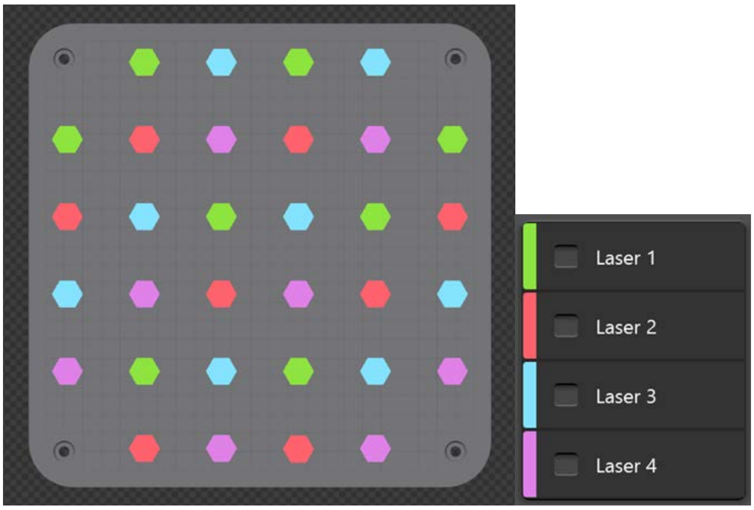


Figure 12 Mechanical property build laser assignment

Four builds were repeated for each material, two using TEMPUS technology, and two using a conventional AM process. All builds for a given material were produced on the same RenAM 500Q Ultra machine, with the same calibration state, using the same powder batch.

One build of each type was subsequently heat treated, providing parts produced in each of the following four scenarios:

- Without TEMPUS technology, as-built
- Without TEMPUS technology and heat treated
- With TEMPUS technology, as-built
- With TEMPUS technology and heat treated

Renishaw-recommended material build parameters were used to produce each build (see Table 3). All builds were produced with a 60 µm layer thickness. The same core parameters were used for builds both with and without TEMPUS technology. Table 4 includes the additional parameters used for the TEMPUS technology builds.

Build parameter	Value
Recoater width	35 mm
Recoater time safe zone	150 ms
Forward speed	100 mm/s
Backward speed	362 mm/s
Elevator dip	0.25 mm
Elevator speed	0.5 mm/s
Minimum layer duration	0 ms

Table 4: TEMPUS technology parameters used for mechanical property testing

Table 5 shows the build times for the conventional and TEMPUS technology builds for each material.

Material	Conventional build time [hh:mm]	Build time with TEMPUS technology [hh:mm]	Build time reduction [hh:mm]	Proportional time saving [%]
Ti6Al4V	10:40	6:59	3:41	34.5
Co28Cr6Mo	9:06	5:37	3:29	38.3
SS316L	10:16	6:29	4:11	39.2
Inco 718	13:10	9:30	3:40	27.9

Table 5: Build times for the mechanical property test samples

3.3.1.2 Heat treatment

The applicable builds were heat treated as per Renishaw's recommended heat treatment profile for each material (see Table 6). For a given material, both the conventional and TEMPUS technology builds were heat treated in the same furnace, under the same cycle at the same time.

Material type	**Value**
Ti6Al4V	• Heat to 800 °C ± 10 °C with a heating rate 13 °C / min. under vacuum. • Hold at 800 °C ± 10 °C for 4 hours under vacuum. • Furnace cool to room temperature under vacuum.
SS316L	Stress Relief • Heat to 450 °C ± 10 °C under argon at rate of 8 °C / min. • Hold at 450 ° for 1 hr under argon. • Air cool to room temperature. Annealing • Heat to 900 °C ± 15 °C under vacuum at rate of 8 °C / min. • Hold at 900 °C for 2 hrs. • Quench under argon to room temperature.
Co28Cr6Mo	Solution treatment (under vacuum) • Heat to 640 °C ± 10 °C at rate of 8 °C / min. • Hold for 15 min. • Heat to 1000 °C ± 10 °C at rate of 8°C / min. • Hold for 5 min. • Heat to 1050 °C ± 10 °C at rate of 8 °C / min. • Hold for 2 hours. • Argon gas quench to below 60 °C ± 10 °C with gas pressure of 2 bar. Annealing (under vacuum) • Heat to 1150 °C ± 10 °C in 120 min (rate of 8 °C / min) • Hold for 6 hours. • Furnace cool to room temperature.
Inconel 718	Solution treatment (under vacuum) • Heat to 980 °C ± 20 °C under vacuum at rate of 13 °C / min. • For parts up to 2.54 cm (1 inch) cross-section, hold under vacuum for 1 hr, plus 1 hr for every additional 2.54 mm (1 inch) cross-section. • Argon gas quench to room temperature with the gas pressure of 1 bar. Ageing treatment (under vacuum) • Heat to 720 °C ± 10 °C under vacuum at rate of 13 °C / min. • Hold for 8 hr under vacuum. • Furnace cool to 620 °C ± 10 °C in 10 min. • Hold for 8 hr under vacuum. • Argon gas quench to room temperature with the gas pressure of 1 bar.

Table 6: Heat treatment profiles

3.3.1.3 Tensile testing

All tensile bar blanks were machined to drawing M-4447-7005-01-A (Figure 13) which is compliant to ASTM E8/E8M. All parts were machined at Renishaw by a single experienced machinist on the same machine tool.

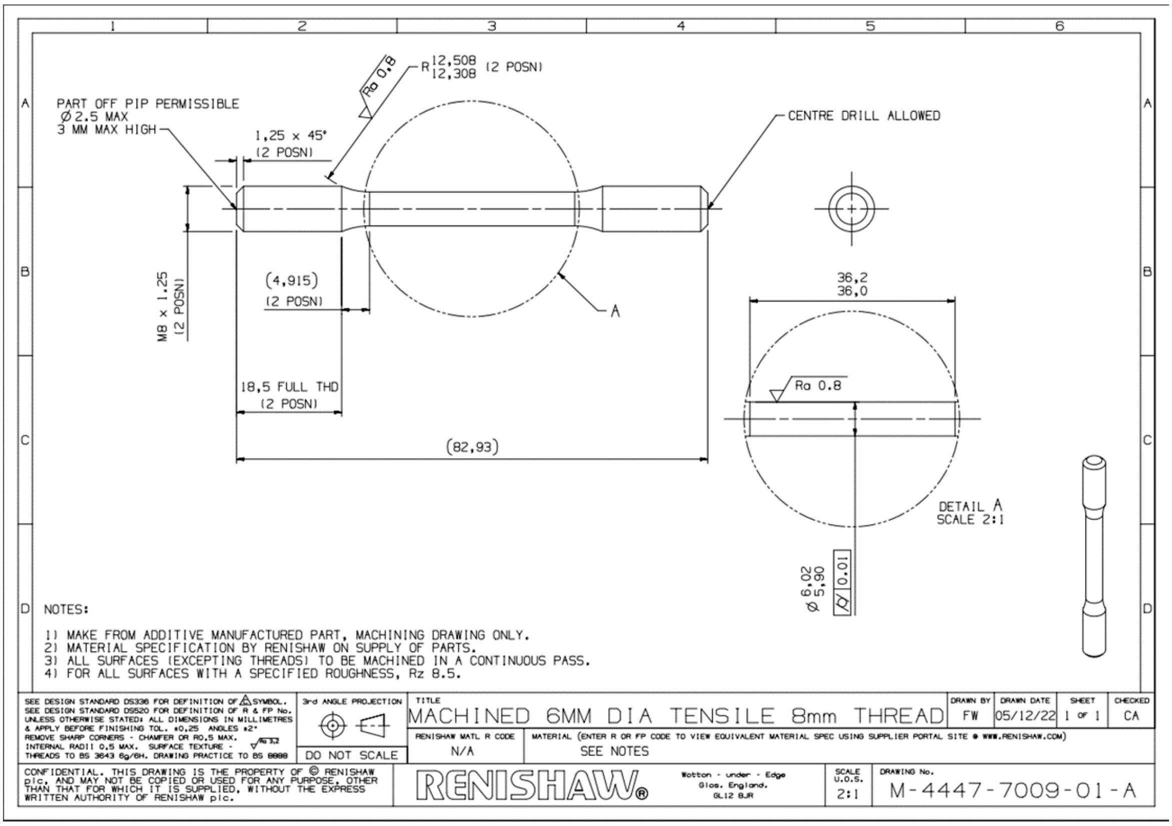


Figure 13 Tensile test specimen dimensions

The machined bars were tensile tested in line with ISO 6892-1 2019 method 1A on an Instron 5984 tensile tester in Renishaw's materials lab.

3.3.2 Results

Figure 14 shows the mechanical property results for all four materials, both with and without TEMPUS technology and in the as-built and heat treated state. See Appendix B: Part properties by material for results broken out by material.

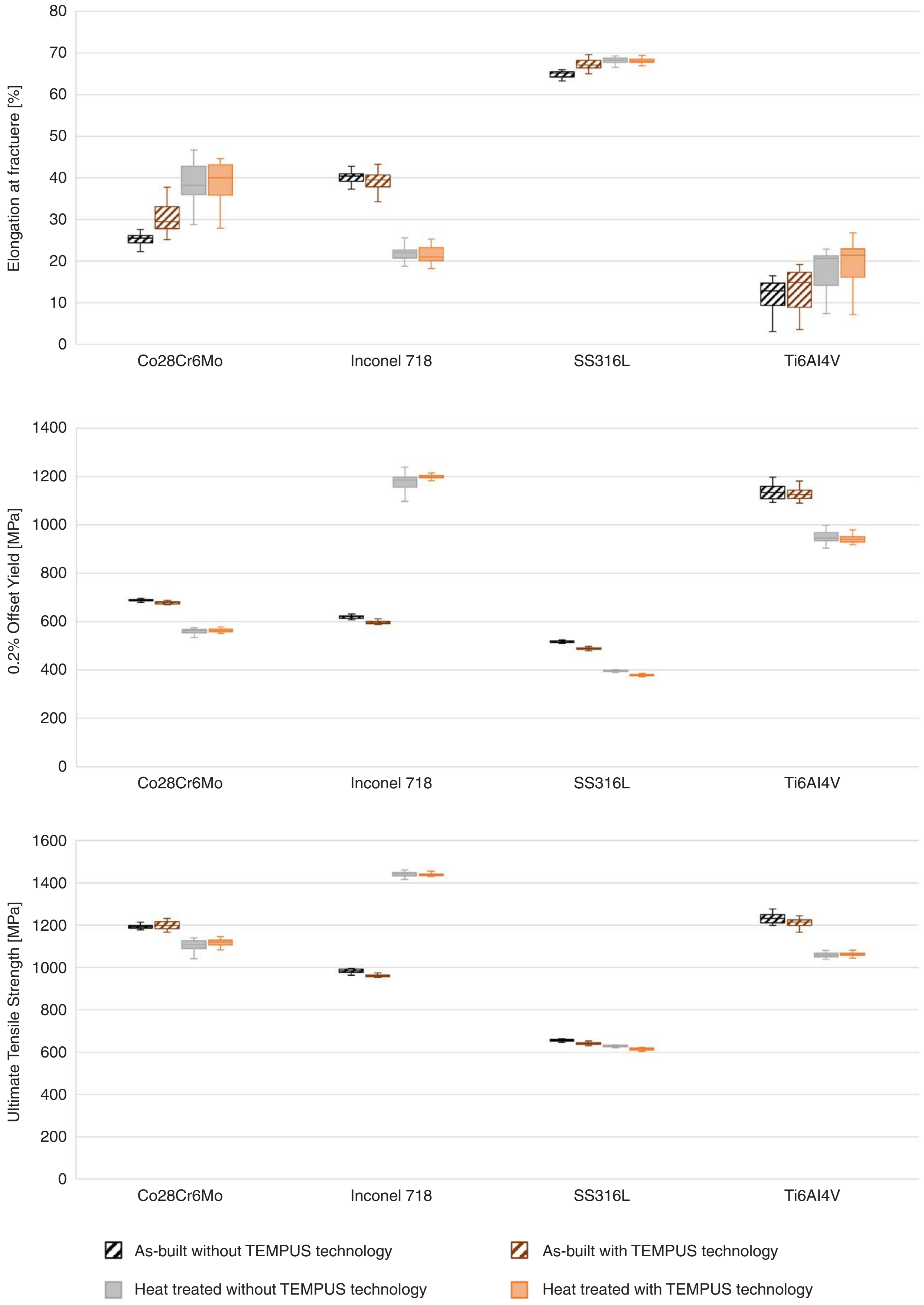


Figure 14 Mechanical properties for all materials, with and without TEMPUS technology and heat treatment

3.3.3 Discussion

The results show no significant differences between mechanical properties for parts built with or without TEMPUS technology in the heat-treated state. Any observable differences are within the margin of error of the test method.

In a small number of cases, there are significant differences between as-built properties for parts built with or without TEMPUS technology. For example, the elongation of Co28Cr6Mo in the as-built state is higher when using TEMPUS technology than without – as shown in Figure 15. However, after heat treatment, there is no observable difference between part properties with and without TEMPUS technology.

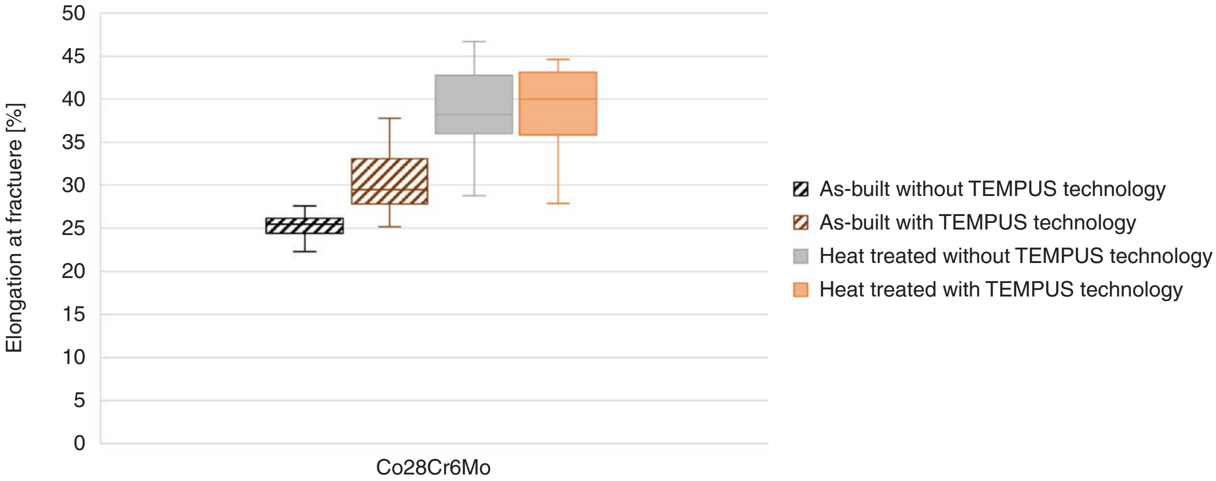


Figure 15 Elongation at fracture for Co28Cr6Mo with and without TEMPUS technology and heat treatment

These results confirm the hypothesis that any difference in as-built microstructure when processing with TEMPUS technology can be eliminated through heat treatment. As such, the mechanical properties for parts built using TEMPUS technology and heat treated are equivalent to conventional AM parts.

These results also do not show any evidence of lack of fusion defects, causing mechanical property reduction, when using TEMPUS technology. This aligns with the hypothesis that TEMPUS technology does not impactfully disrupt gas flow in the proximity of the melt pool.

3.4 Volumetric density

3.4.1 Method

The same AM builds and heat treatment used for mechanical property testing were used to produce density test samples; see Section 3.3.1 for details.

The eight hexagonal artefacts from the furthest left and right positions on the build plate were selected for volumetric density analysis as circled in Figure 16. These locations were selected as they represent the positions most likely to show evidence of gas flow disruption due to recoater movement, as the layer sequencing means these artefacts would be processed while the recoater is passing over the powder bed.

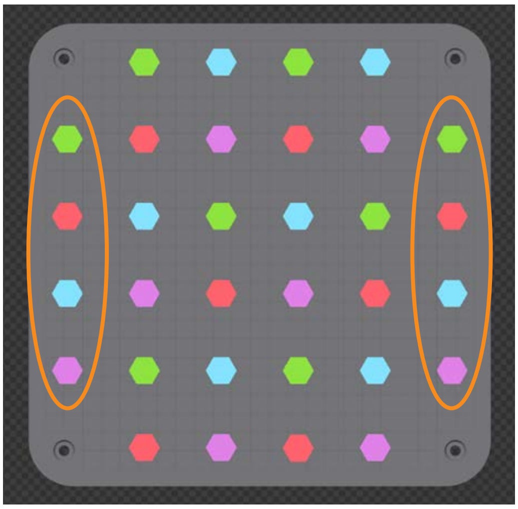


Figure 16 Density sample locations (circled)

These eight 8 artefacts were potted, sectioned and polished along the XY and XZ planes.

The volumetric density was then assessed using an optical gauging probe (OGP) (model: Zip Light 300), which was verified in accordance with ISO 10360-7:2011. Figure 17 shows an example of the optical images taken of a polished sample (left) and the density analysis which highlights porosity (right).

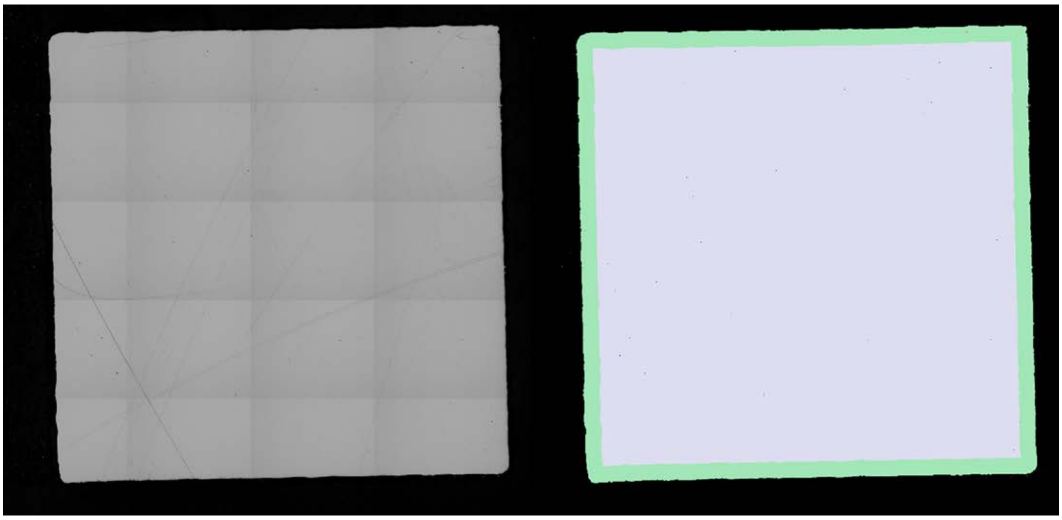


Figure 17 Example OGP image and density analysis

3.4.2 Results

Figure 18 shows the volumetric density results for all the tested materials in the as-built and heat treated states, both with and without TEMPUS technology.

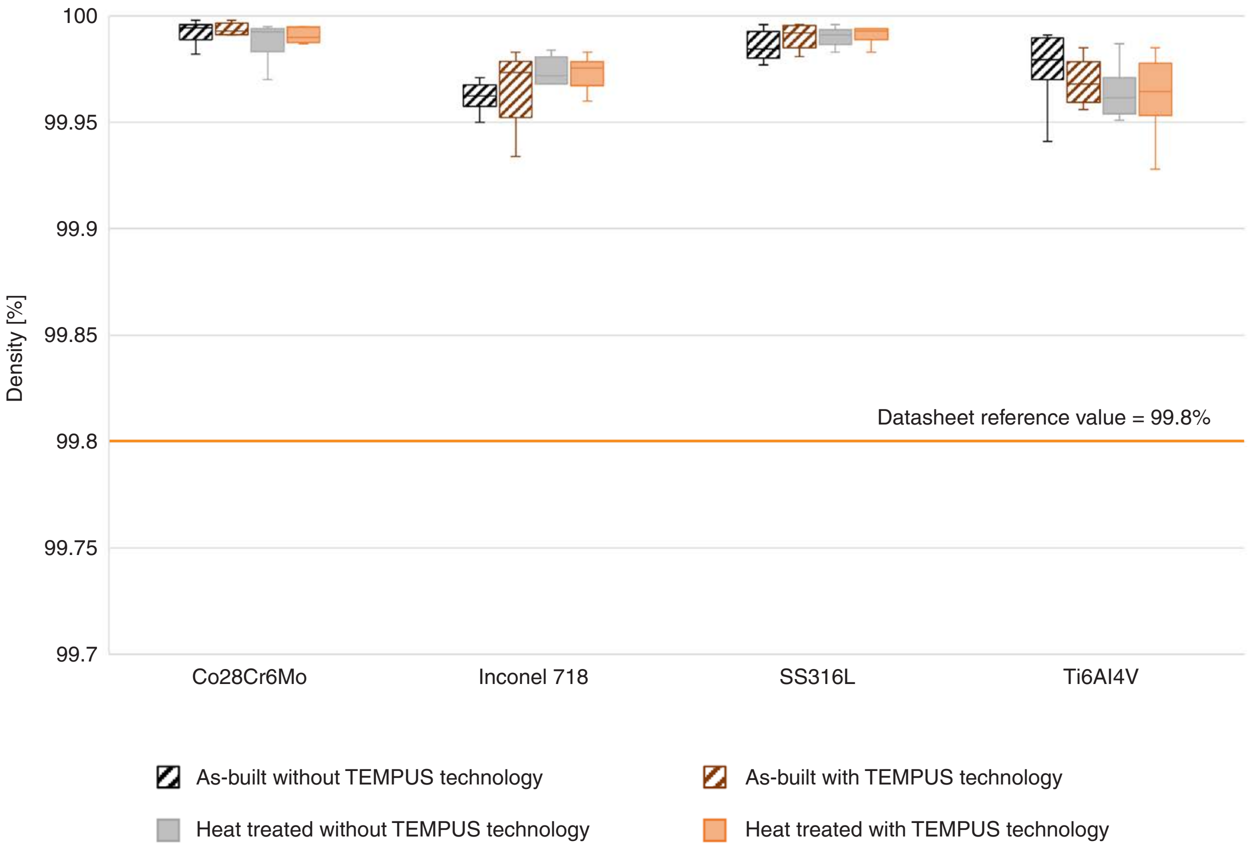


Figure 18 Density results for all materials, with and without TEMPUS technology and heat treatment

3.4.3 Discussion

The volumetric density results show no significant difference between parts produced with or without TEMPUS technology. All results significantly exceed the datasheet reference value of 99.8%. Any observable variation is within the expected margin of error of the test method.

As hypothesised, and supported by the mechanical property results, there is no evidence of lack of disrupted gas flow in the melt pool proximity or fusion defects caused by TEMPUS technology.

3.5 Hardness

3.5.1 Method

The same AM builds and heat treatment used for mechanical property testing were used to produce hardness test samples; see Section 3.3.1 for details.

The eight hexagonal artefacts used for evaluated volumetric density were subsequently used to test hardness through microindentation. Testing was carried out in accordance with ASTM E384-22 using a Buehler Wilson VH3100 Vickers hardness tester in Renishaw's materials lab. Samples were tested in both the XY and XZ planes, 12 indentations were made per test site and averaged[5] for a total of 16 data points per material for each of the four test scenarios (with and without TEMPUS technology, as-built and heat treated).

[5] An average is taken to account for any indentations falling on grain boundaries.

3.5.2 Results

Figure 19 shows the Vickers hardness test results for the five test materials in both the as-built and heat treated states, produced with and without TEMPUS technology.

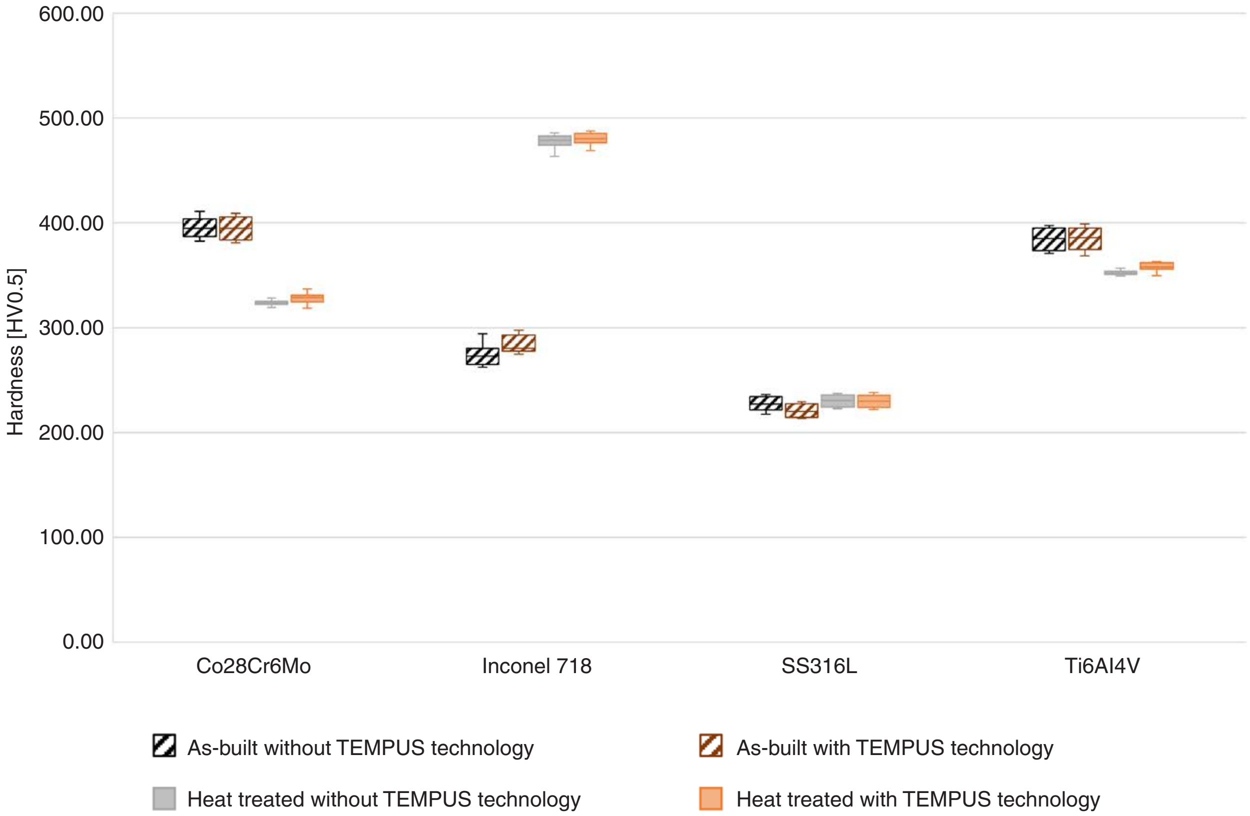


Figure 19 Hardness results for all materials, with and without TEMPUS technology and heat treatment

3.5.3 Discussion

The hardness results closely match the mechanical property findings; there were no significant differences between hardness values for parts built with or without TEMPUS technology in the heat-treated state. Any observable differences are within the margin of error of the test method.

In a small number of cases, there are significant differences between as-built hardness for parts built with or without TEMPUS technology. For example, Inconel 718 demonstrates higher hardness values in the as-built state when using TEMPUS than without. However, after heat treatment, there is no observable difference.

As discussed in Section 3.2, a difference in metallic microstructure due to the changes in thermal condition when using TEMPUS technology would be expected to drive differences in physical properties in the as-built state, including hardness. However, these results further confirm the hypothesis that any such differences in as-built microstructure can be eliminated through heat treatment. As such, part hardness when built using TEMPUS technology and heat treated are equivalent to conventional AM parts.

3.6 Surface roughness

3.6.1 Method

An array of 16 trapezoid artefacts were built, covering the build volume (as per Figure 20). The trapezoids were built with their primary axis aligned with the X and Y machine axes to evaluate the most extreme scenarios for gas flow, recoater and scan direction interaction. The build was repeated using conventional processing and with TEMPUS technology enabled. Neither build was heat treated or further post-processed. Testing was limited to a single material (SS316L) at this stage.

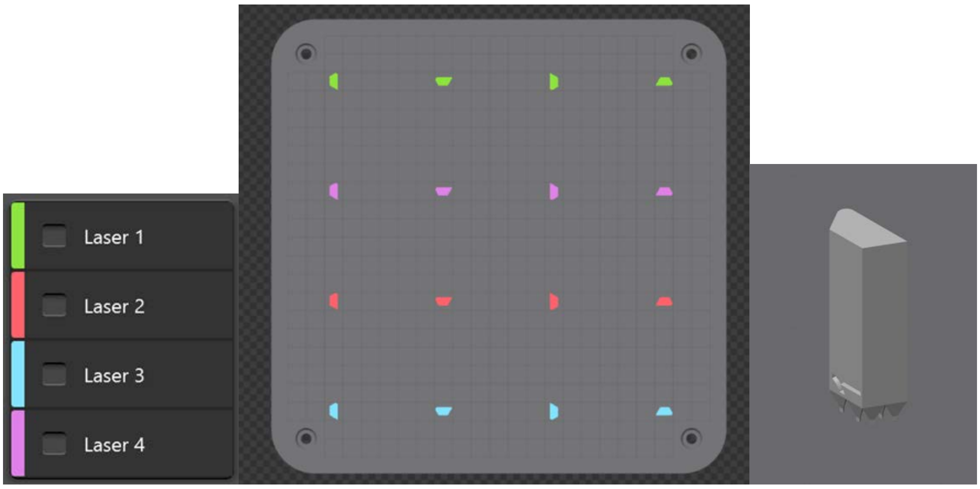


Figure 20 Surface finish test build layout and artefact

The surface roughness of the trapezoids in the vertical direction (Z) were subsequently measured using a surface profilometer in accordance with ISO 4287:1997 in Renishaw's material lab.

3.6.2 Results

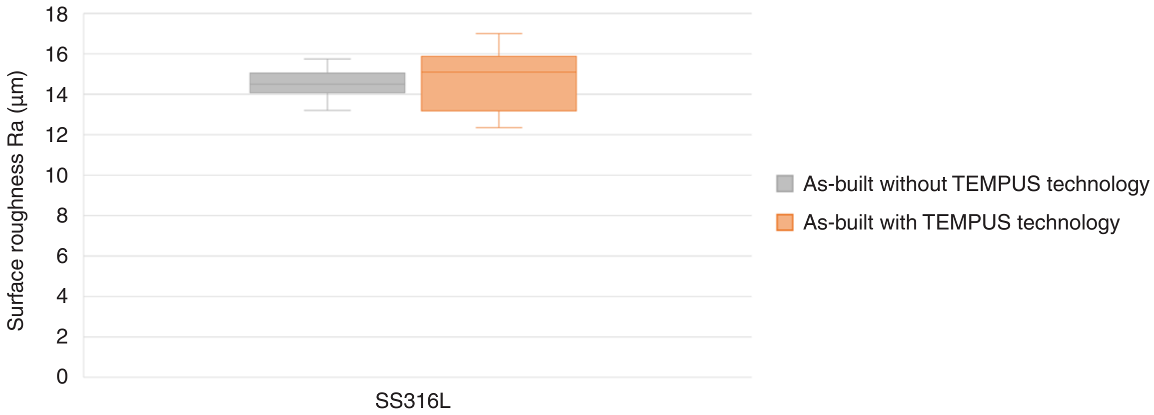


Figure 21 Surface roughness for SS316L samples in the as-built state with and without TEMPUS technology

3.6.3 Discussion

The mean surface roughness exhibited when using TEMPUS technology (14.72 µm Ra) was approximately equal to conventional processing (14.45 µm Ra). The bigger range of values seen when using TEMPUS technology is within the expected uncertainty margin for this test, given the relatively rough nature of AM surfaces.

As outlined in Section 3.2, reduced layer times will result in elevated powder bed temperatures for a fixed geometry which is typically associated with increased surface roughness. This effect will be heavily geometry dependent, and in this case there is no evidence that TEMPUS technology impacts surface roughness.

3.7 Geometric accuracy

3.7.1 Method

3.7.1.1 AM build set-up

The Renishaw standard acceptance test build was built both conventionally and with TEMPUS technology. The build contains a series of geometric measurement artefacts, designed for CMM inspection (as circled on Figure 22). One laser was assigned to each artefact as per Figure 23. The build was repeated using conventional processing and with TEMPUS technology enabled. Neither build was heat treated or further post-processed. Testing was limited to a single material (SS316L); as outlined in Section 3.2.3, there is no engineering rationale for the material to affect this property.

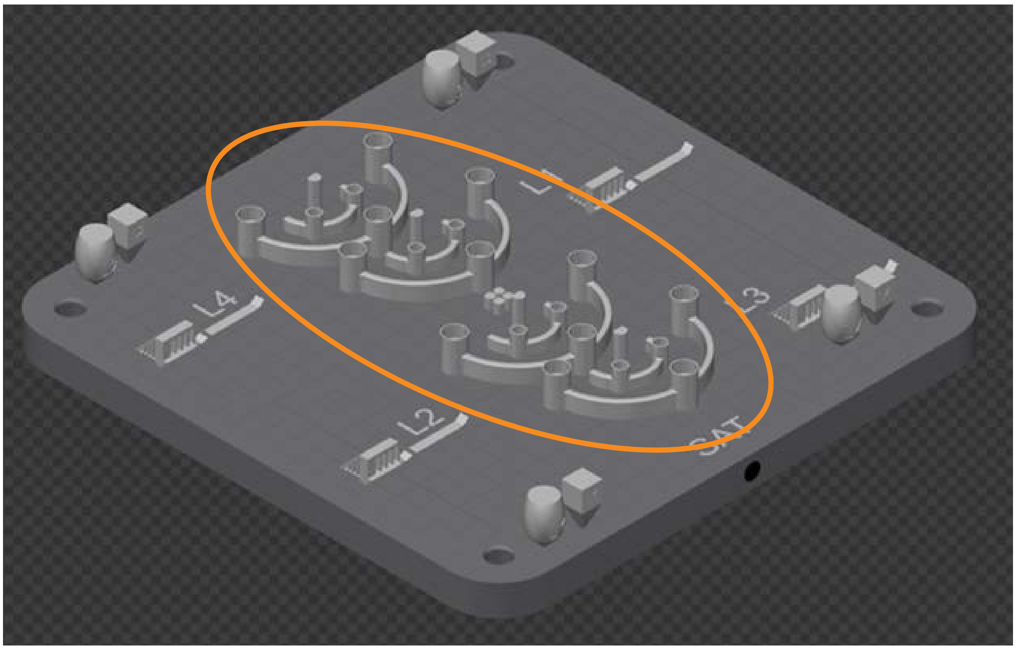


Figure 22 Geometric accuracy test build with measurement artefacts circled

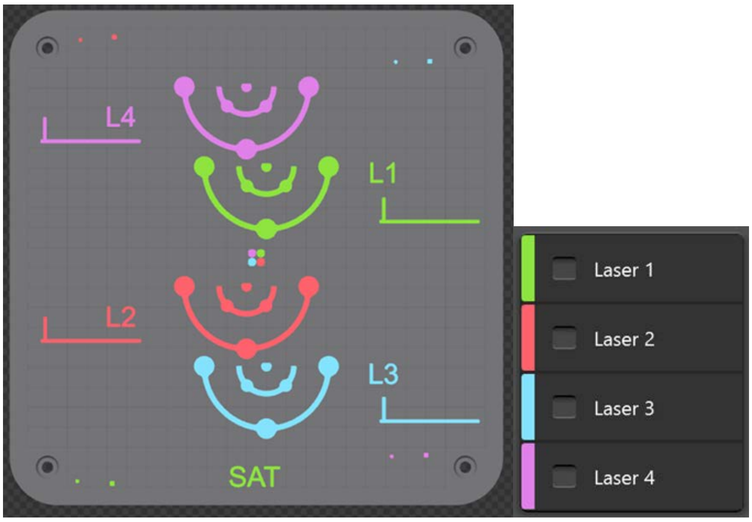


Figure 23 Laser assignment for the geometric accuracy build

The builds were produced on a RenAM 500Q using SS316L stainless steel. The run time for the TEMPUS technology build was 58 minutes, which was 35% less than the conventional build (1 hour 29 minutes). The TEMPUS technology parameters used were the same as for the mechanical property testing (see Table 4) – including a Z-axis elevator dip of 0.25 mm.

For the TEMPUS technology build, the Z-axis was moving during the laser processing of the measurement artefacts (as described in Figure 2) to test the impact on geometric accuracy.

While still attached to the build plate, the measurement artefacts were inspected using an AGILITY S co-ordinate measuring machine (CMM) with a REVO-2 probe, calibrated in accordance with ISO10360-2:2009.

The CMM inspection program inspected multiple features per artefact (194 total features per build), including cylinder diameters, wall thicknesses, absolute position, feature height, arc radiuses and lengths between features. The inspection was performed ten times per build and the mean deviation from nominal was calculated for each measured feature.

3.7.2 Results

Figure 24 shows the deviation from nominal for the 194 measured features, for both the conventional build and the TEMPUS technology build.

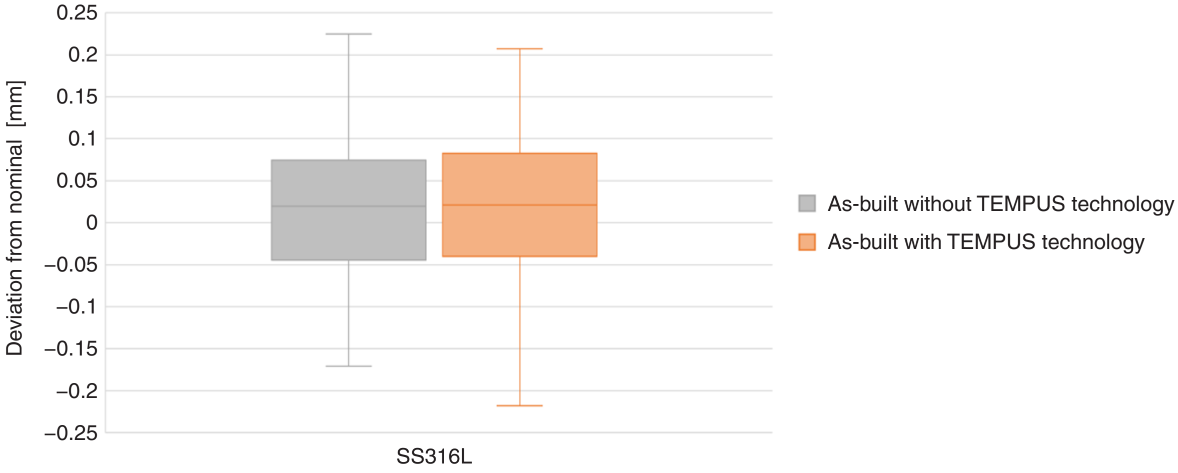


Figure 24 Geometric accuracy errors both with and without TEMPUS technology

3.7.3 Discussion

The close correlation between the results for the two build types indicates that TEMPUS technology had no effect on part geometric accuracy. The distribution of error is common to both scenarios, and any deviation from nominal is within expected performance. The results confirm the hypothesis that the dynamic Z-axis movement of TEMPUS technology does not result in any change in part accuracy due to the compensation performed by the RenAM 500 system.

4. Conclusion

TEMPUS technology has been demonstrated to offer a significant productivity boost over conventional AM processing. Through a reduction in recoating time and ability to fire the laser(s) while the recoater is preparing the powder layer, build times can be reduced by up to 58%.

In terms of part properties, a comparative study of conventional and TEMPUS technology processing methods has shown that both approaches achieve equivalent material properties after heat treatment. Further the results show TEMPUS technology does not compromise part quality in favour of productivity.

5. Appendix A: TEMPUS technology FAQs

5.1 What is the impact for qualification in regulated markets?

In terms of machine qualification, TEMPUS technology can be evaluated in the same manner as other build parameters (such as laser power). TEMPUS technology parameters are set as part of the build file and can be validated as a variable.

For existing validated processes, TEMPUS technology parameters can be adjusted to closely approximate conventional AM processing (i.e. not firing the laser(s) while the recoater is above the powder bed). This results in a per-layer build time reduction of approximately 2.5 seconds (as described in Section 2). Additionally, a minimum layer duration can be set in order to prevent the process from exceeding a validated build-rate range.

5.2 What is the impact for service and maintenance?

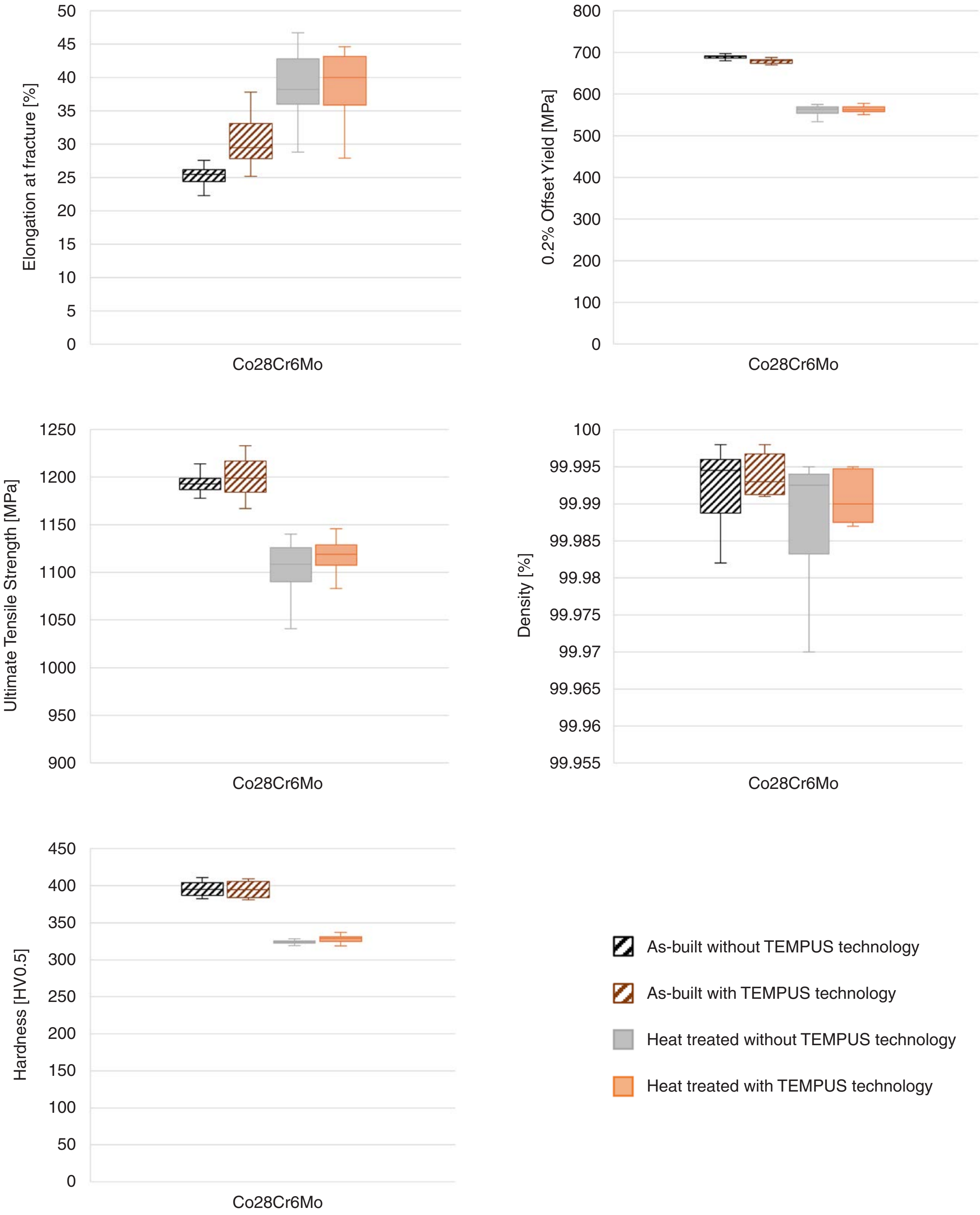
The hardware components of TEMPUS technology have been designed to enable the maximised performance of TEMPUS technology without changes in expected component life, as confirmed by extensive testing.

With one exception (see below), there are no changes required in terms of user machine maintenance.

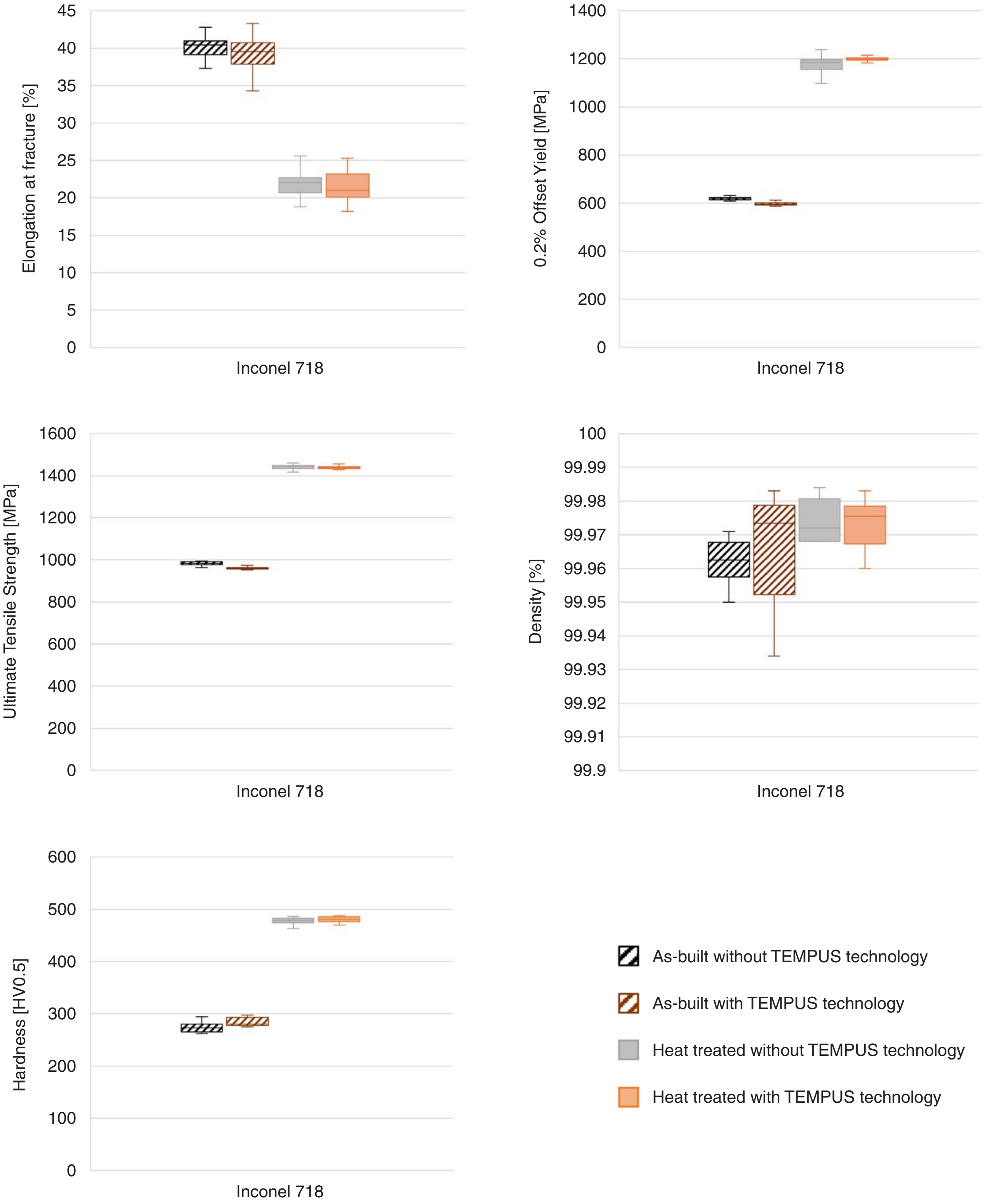
Due to the specific characteristics of the material and process, AlSi10Mg users who are operating at very high throughput may find that their sieve mesh (on recirculating machines) needs to be more regularly changed. A customer process and mesh kit has been created to enable users to change the sieve mesh themselves – part number A-6521-0627 (the kit comes with the user instructions).

6. Appendix B: Part properties by material

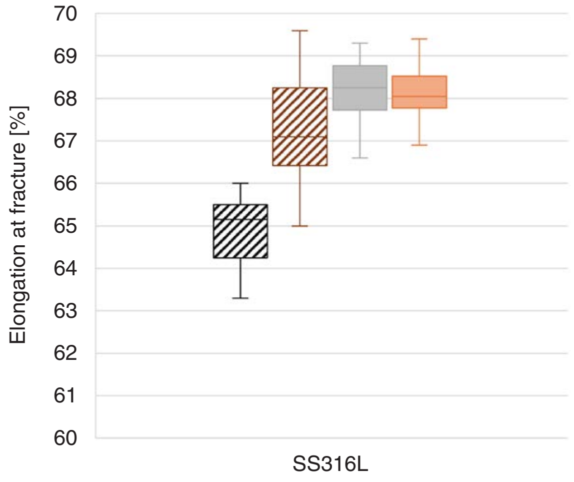
6.1 Co28Cr6Mo

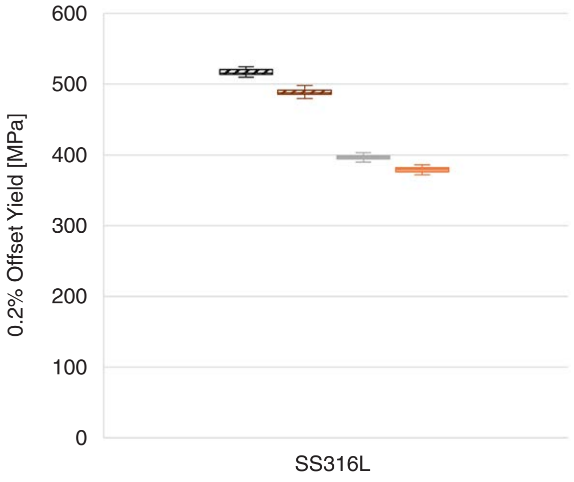


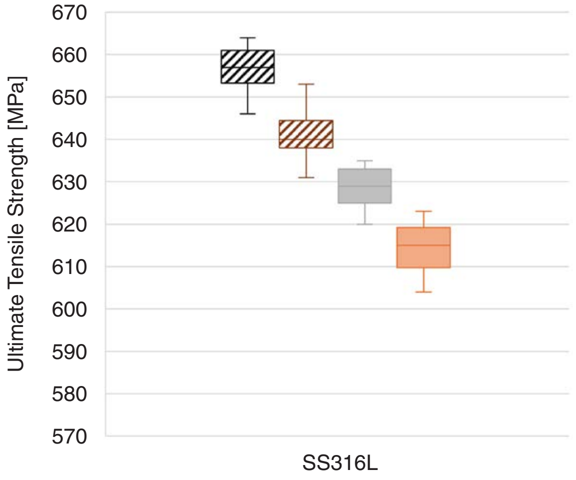
6.2 Inconel 718

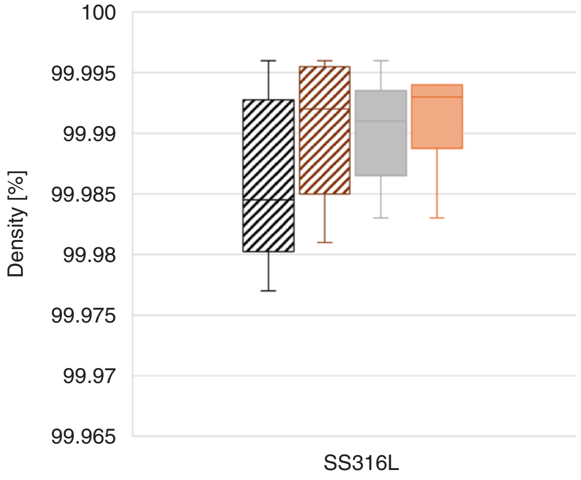


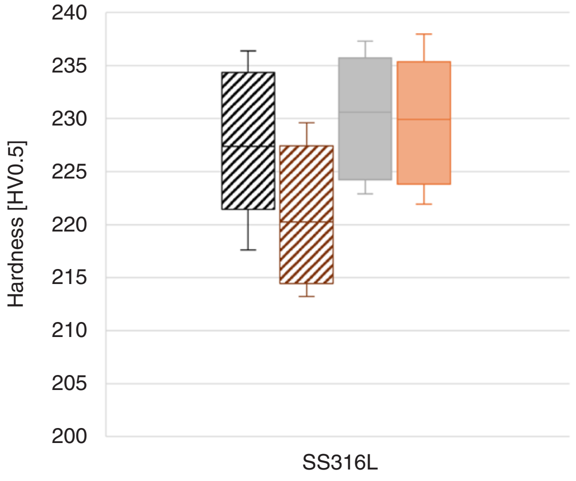
6.3 SS316L











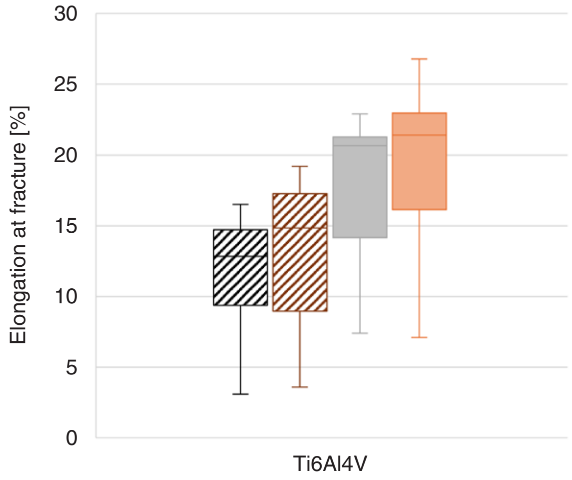
▨ As-built without TEMPUS technology

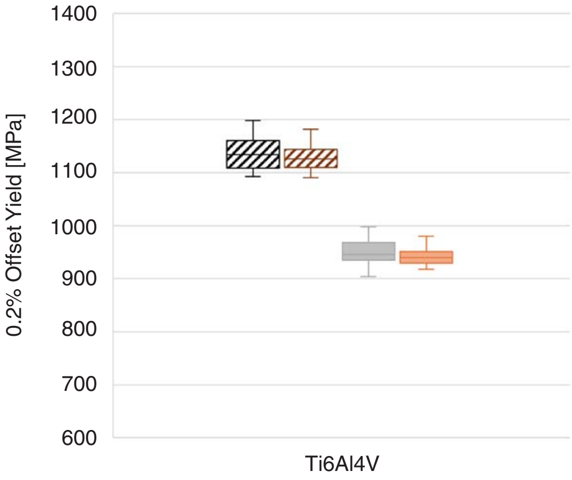
▨ As-built with TEMPUS technology

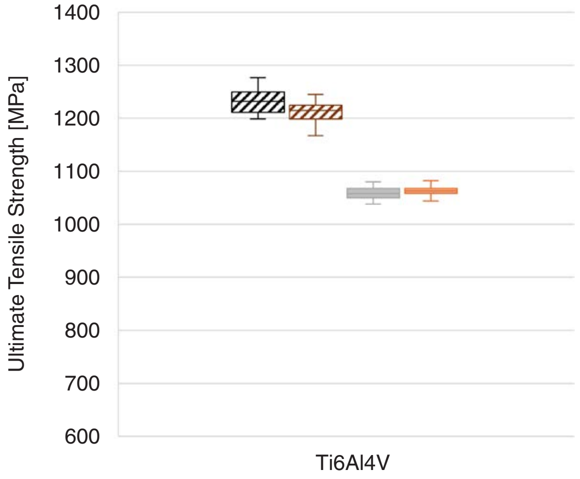
■ Heat treated without TEMPUS technology

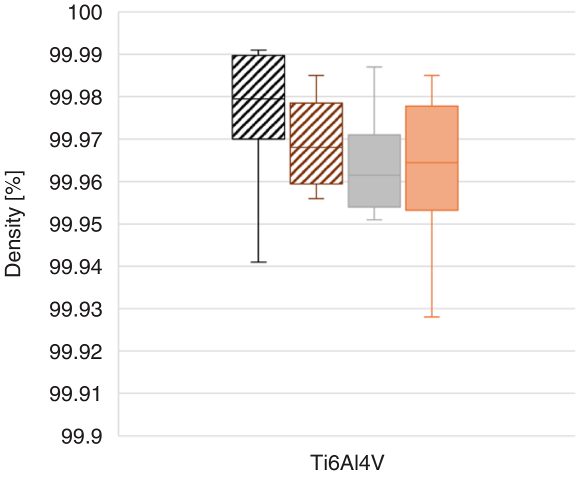
■ Heat treated with TEMPUS technology

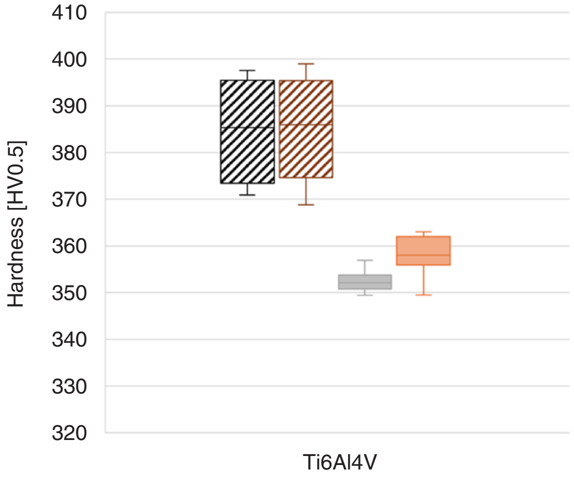
6.4 Ti6Al4V











▨ As-built without TEMPUS technology

▨ As-built with TEMPUS technology

■ Heat treated without TEMPUS technology

■ Heat treated with TEMPUS technology

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