The Status of Research on Structural Integrity of Additive Manufacturing in Steels and Aluminium Alloys

White Paper

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Abstract

Additive manufacturing (AM) is a revolutionary production method that transforms design data into physical components, by layering materials to achieve precise shapes with minimal waste and without the need for costly specialised tooling. This technology not only enables significant product re-designs but also allows for the creation of novel material properties.

Despite significant research progress, AM of both steel and aluminium components face persistent challenges in ensuring consistent structural integrity.

This White Paper aims to identify the status of research in relation to structural integrity of AM steels and aluminium alloys. In addition, it identifies key challenges in ensuring structural integrity, as well as looking at Standards development and future research needs. Conclusions are also drawn for consideration.

Finally, an overview of the research undertaken by PhD students, working within the field of structural integrity, as part of TWI's Fatigue Integrity Management (FIM) Section, is also presented. Here, work on Ti-6Al-4V is also included.

1. Introduction

Research on the structural integrity of additively manufactured (AM) parts has advanced significantly in recent years, with extensive investigations into both steel and aluminium alloys. Current studies reveal that while AM technologies offer tremendous potential for manufacturing complex components with improved material efficiency, challenges remain in ensuring consistent mechanical properties and long-term performance.

Figure 1 Additive manufacturing *(Courtesy of TWI Ltd.)*

For steel components, research has focused on Wire Arc Additive Manufacturing (WAAM) processes and their effects on fatigue resistance and corrosion behaviour, particularly for marine applications.

Research into titanium alloys, typically used in aerospace, medical and energy industries, concentrate on the continual development of process optimisation and powder waste reduction for processes such as selective laser melting (SLM), selective electron beam melting (SEBM) and laser metal deposition (LMD). Aluminium alloy research using processes as those for titanium, has concentrated on understanding how build parameters and orientation influence defect formation and subsequent mechanical properties. Despite substantial progress, researchers consistently identify the need for more comprehensive testing data to overcome barriers to widespread industrial adoption, with standardisation efforts still developing for aluminium-specific applications.

2. Challenges in Ensuring Structural Integrity

Despite significant research progress, AM of both steel and aluminium components face persistent challenges in ensuring consistent structural integrity. For aluminium alloys, researchers have identified several material-specific difficulties that complicate the manufacturing process and potentially compromise structural performance [1]. These challenges include the relatively low weight of powder particles, poor flowability characteristics, high thermal conductivity, and high tendency to oxidation forming high melting point aluminium oxide. This combination of properties increases the risk of defects in AM aluminium components, which can significantly degrade mechanical performance, particularly under fatigue loading conditions where small imperfections often initiate failure.

The thermal management aspects of AM present critical challenges for both steel and aluminium processes. The layer-by-layer construction inherent to additive techniques creates complex thermal gradients and cycling that can induce residual stresses and microstructural heterogeneity throughout the component. For WAAM processes used with steel (Figure 2), the repetitive welding results in high stress concentrations between adjacent welded layers, non-uniform thermal gradients and complex residual stress fields that can significantly affect mechanical behaviour and fatigue performance [2]. Similarly, aluminium components manufactured using powder bed fusion (PBF) experience variations in thermal history based on their build orientation, leading to differences in defect type, size, and distribution that directly impact structural integrity [1].

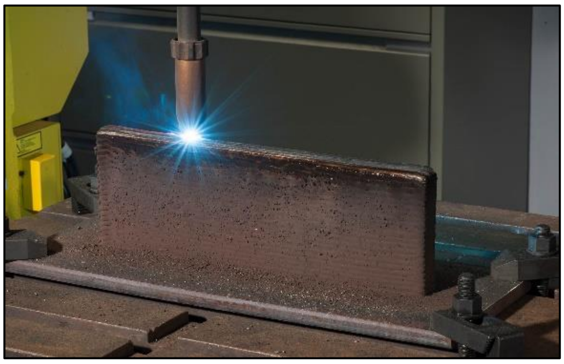


Figure 2 WAAM performed at TWI Ltd *(Courtesy of TWI Ltd.)*

The specification and standardisation landscape for AM components presents additional complexity compared to conventionally manufactured parts. Current approaches guided by ASTM and ISO Standards require more engineering decisions throughout the manufacturing process than typically encountered with traditionally produced components [3]. These decisions encompass material selection, process choice, build orientation, and post-processing requirements, all of which influence final structural integrity. Notably, while ASTM has established Standards for several commonly used materials in powder bed fusion AM systems [4-6], there are currently none specific to aluminium [3]. This standardisation gap complicates the qualification of aluminium AM components for safety-critical applications, highlighting the need for continued development of comprehensive, material-specific standards.

A breakdown of key issues across both materials is presented in the Table.

These challenges underscore the need for interdisciplinary research to bridge gaps in material science, process engineering, and non-destructive testing (NDT) for AM components.

Table Key challenges across both materials facing structural integrity in AM

Material	Challenge	Details
Steel and Aluminium alloys	Defect formation	**Porosity**: Gas pores and lack of fusion defects are prevalent in both materials, compromising fatigue life and mechanical performance [7-9]. **Cracks**: Volumetric cracks (e.g. solidification) and residual stress-induced cracking are critical concerns, particularly in high-stress applications [7] [10]. **Lack of Fusion**: Poor interlayer bonding in laser powder bed fusion (LPBF) or wire arc additive manufacturing (WAAM) creates weak zones and crack initiation sites [7-8] [10].
	Post-Processing Limitations	Post-build treatments (e.g., heat treatments, machining) can introduce new defects, such as cracks from grinding marks or distortion during stress relief [7] [10].
	Standardisation gaps	Limited material-specific standards for AM processes, especially for aluminium, hinder qualification for safety-critical applications [1] [11].
Steel	WAAM process defects	**Humping Defects & Material Overflow**: Irregular bead geometry and unstable deposition in WAAM lead to poor surface quality and internal flaws [12]. **Residual Stresses**: High thermal gradients during layer-by-layer welding create residual stresses, increasing susceptibility to fatigue failure [10] [12].
	Microstructural heterogeneity	Variations in grain structure and phase distribution between welded layers affect mechanical consistency, especially in large-scale components [10] [12-13].
	Environmental degradation	Corrosion-fatigue interactions in marine environments require specialized testing to predict component lifespans [10].
Aluminium alloys	Material limitations	**Oxidation & Reflectivity**: Aluminium's high reflectivity and rapid oxidation during LPBF reduce laser absorption, leading to incomplete melting and defects [9] [11]. **Powder Handling**: Lightweight particles with poor flowability and high affinity with oxygen complicate powder-bed processes [1] [11].
	Build orientation effects	Horizontal builds exhibit higher defect concentrations (e.g., lack-of-fusion, porosity) than vertical builds due to thermal history variations. Specially developed powders (e.g. Addalloy® 5T (AD1)) show lower defect density, hence improved performance [1] [10]. [14 – 16]
	Fatigue performance	As-built aluminium parts have 90% shorter high-cycle fatigue life than wrought materials due to defect-driven crack initiation. Post-processing (e.g., hot isostatic pressing) is essential but adds cost [10].
	Alloy development needs	High-strength alloys (e.g. AlSi10Mg, QuesTek Al, and AlF357) are now being overtaken by new formulations (e.g. AD1) which are being optimised for AM but require extensive validation [1] [11] 14 – 16]

3. Manufacturing Process Selection and Impact

The selection of appropriate AM processes significantly influences the structural integrity of both steel and aluminium components. Current research has explored multiple process options for each material category, with distinct advantages and limitations for structural applications. For aluminium components, processes include: PBF (Figure 3), where fine aluminium powder is selectively melted or sintered using laser (LB-PBF) or electron beam (EB-PBF) energy sources [17]; Directed Energy Deposition (DED), which melts aluminium wire or powder through focused thermal energy; Binder Jetting, which utilises metal injection moulding powders sintered after deposition, and Cold Spray (Figure 4), where aluminium powder is accelerated to supersonic speeds to create components without melting the material [3].

Figure 3 LB-PBF component manufactured at TWI Ltd *(Courtesy of TWI Ltd.)*

Each manufacturing process introduces specific structural considerations that ongoing research aims to characterise and address. PBF, while offering excellent geometric precision, can create gas pores [18-19] or lack of fusion defects, potentially compromising fatigue performance. Cold spray process avoids melting-related challenges but relies on mechanical bonding rather than metallurgical bonding, negatively influencing structural behaviour. The increasing variety of manufacturing options necessitates comprehensive comparative studies to establish process-specific performance expectations and develop appropriate quality assurance protocols for different structural applications.

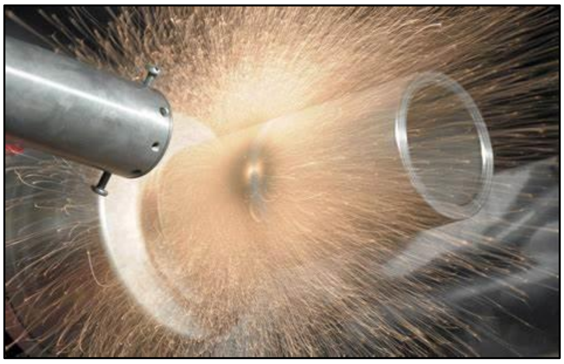


Figure 4 Cold spray performed at TWI Ltd *(Courtesy of TWI Ltd.)*

The influence of manufacturing parameters on structural integrity represents another critical research dimension for both steel and aluminium components. Process variables such as energy input, scan strategy, layer thickness, and cooling rates significantly affect microstructural development and defect formation, directly impacting mechanical properties and failure resistance. Current research emphasizes the importance of optimising these parameters for specific material-process combinations to minimize defects while maximizing performance. This parameter optimisation represents a complex multi-variable challenge that requires sophisticated experimental design approaches and continues to drive significant research investment across both academic and industrial settings.

4. Process-Related Challenges

- **Thermal Management**
  The high thermal conductivity of aluminium may result in uneven cooling, while steel's WAAM process induces complex residual stress fields [1] [10] [12].
- **In-Process Monitoring**
  Real-time detection of defects (e.g. porosity, cracks) remains limited, complicating quality assurance [7] [9].

- **Parameter Optimisation**
  Balancing laser power, scan speed, and layer thickness is critical to minimize defects but requires trial-and-error approaches [9] [11].

5. Steel-Based Additive Manufacturing Research Developments

WAAM has emerged as a prominent technology for steel component fabrication, particularly for large engineering structures that benefit from the material efficiency and reduced lead times offered by additive processes. Recent research has comprehensively investigated the structural integrity of WAAM-built steel specimens, specifically focusing on materials such as ER70S-6 and ER100S-1 steels [2]. These investigations have assessed multiple mechanical properties including hardness, tensile behaviour, fracture toughness, and fatigue crack growth characteristics to establish performance baselines for industrial implementation. The manufacturing method shows significant potential to improve material design and efficiency of structural components, with subsequent reductions in production costs and lead times that have already attracted adoption in aerospace and automotive industries [2].

The unique challenges presented by WAAM technology for steel components stem from its manufacturing process, which involves repetitive welding that creates high stress concentrations between adjacent layers and complex residual stress fields throughout the component. This manufacturing characteristic necessitates thorough structural integrity assessment, as welded joints in structures are known to be weak points susceptible to fatigue failures and crack initiation [2]. Current research has therefore expanded beyond basic property characterization to include specialized studies on fatigue performance under various loading conditions, providing crucial data for predicting component lifespans in operational environments.

A distinctive focus of recent steel AM research has been the investigation of environmental effects on structural integrity, particularly for marine applications. Researchers have conducted corrosion-fatigue crack growth assessments and examined the fracture characteristics of components previously exposed to corrosive environments, directly addressing the needs of industries like offshore wind construction [2]. This application-specific approach represents an important development of the technology, moving beyond generic property characterization and toward performance metrics that directly inform adoption decisions for particular operational contexts. Comparative assessments between WAAM-built components and traditionally manufactured wrought materials [20] further enhance understanding of the relative advantages and limitations of these manufacturing approaches under demanding environmental conditions.

6. Aluminium Alloy Additive Manufacturing Advancements

Recent advancements in AM of aluminium alloys have led to their use providing increased support in sectors such as aerospace, automotive, healthcare, and consumer goods. New AM-specific alloys such as those containing scandium (Sc) or tailored with custom blends (e.g., Al-Cu, Al-Mg, Al-Si) are being produced, in order to overcome challenges like hot cracking and low ductility, while providing improved strength and mechanical performance.

Breakthroughs in research include novel aluminium powders with finer, more uniform particle sizes, enhancing flowability, build rates, and mechanical properties. A more eco-friendly use of recycled aluminium is also gaining traction, reportedly offering up to 25% cost savings while maintaining comparable performance.

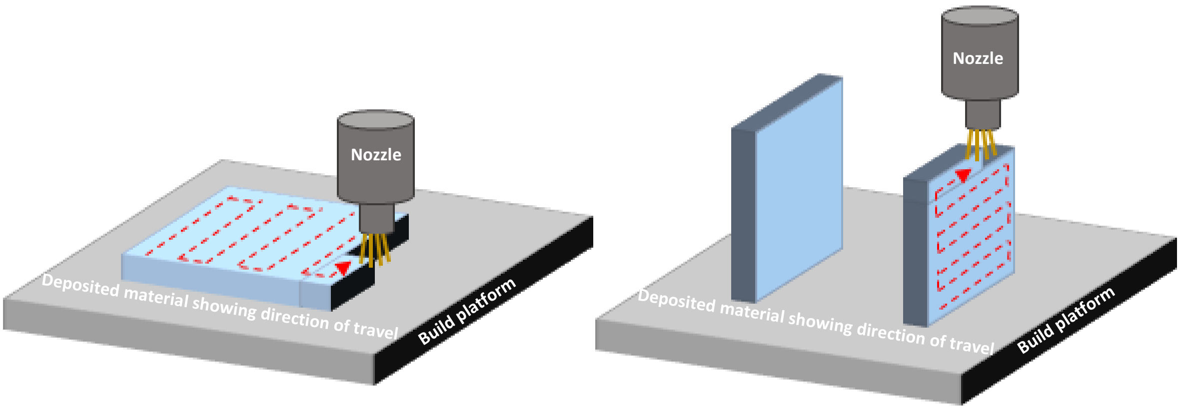
The AM market is one that has been growing rapidly, with the likes of aerospace and automotive industries being the main drivers that benefit from aluminium's excellent strength-to-weight ratio and corrosion resistance [21]. The advancements made are helping make aluminium AM a practical, cost-effective solution for strong, lightweight, and complex parts across multiple industries.

Aluminium alloys used in AM often differ from conventional aluminium classifications, with specialised formulations like AlSi10Mg, AlSi12, AlSi7Mg0.6, and AlSi9Cu3 developed to improve processing and performance [3].

A continued challenge facing the use of aluminium alloys (and steels) relates to build orientation, e.g. horizontal and vertical deposition, Figure 5. The different build directions create unique thermal gradients during layer deposition, altering cooling rates and solidification paths. This controls grain growth direction, residual stress development, and the prevalence of certain defects, which can affect the final part's quality and mechanical performance. For example, detailed studies on AM aluminium alloys [14 - 16] such as AlSi10Mg, AlF357, and others have shown that:

- Build orientation affects defect density and distribution, with horizontal builds often showing more lack-of-fusion, due to insufficient overlap between layers, and higher defect concentrations from increased gas entrapment as compared to vertical builds.
- Vertical build directions in aluminium alloys promote columnar grain growth, which can promote segregation and hot cracking along grain boundaries during rapid solidification.
- Porosity morphology and distribution vary with build orientation, influencing mechanical properties like tensile strength and fatigue behaviour.
- The anisotropy and surface roughness related to build angle have also been studied in aluminium alloys manufactured by laser powder bed fusion (L-PBF).
- The effect of build orientation is interlinked with energy input, laser scan speed, and layer thickness. Suboptimal parameters in certain orientations aggravate void formation, insufficient bonding, and poor surface quality.

Build orientation must therefore be carefully chosen and, where possible, optimized together with process parameters to minimize defect formation and achieve desirable mechanical properties.



a) b)

Figure 5 Schematic showing two common build directions, a) Horizontal and b) vertical.

Another persistent challenge is oxidation, affecting both process stability and final mechanical properties. During processes such as WAAM and SLM, a native oxide layer forms on the surface which following repeated solidification cycles, can become thicker, interfering with metallurgical bonding and increasing the risk of lack of fusion and porosity [22]. Careful management of oxidation is therefore required to avoid impinging fatigue performance, corrosion resistance and general weld integrity.

The comparative performance for different aluminium alloys represents another important research area. Findings indicate that newer formulations like Addalloy® 5T (AD1) outperform traditional options such as AlSi10Mg, QuesTek Al, and AlF357 in fatigue performance regardless of build orientation [1]. This is considered to be due to AD1's combination of lower defect density, high tensile strength, and higher elongation. This shows that use of specially developed powders specifically optimized for additive processes can yield significant performance improvements.

Whilst the majority of studies have been limited to only on a few alloys, researchers using nanoparticles of nucleants that control solidification during AM, have been applied to high strength aluminium alloys thought previously to be incompatible with the process (7075 and 6061 series), with promising results using SLM [23].

These comparative studies provide crucial data for material selection decisions, enabling more informed application of aluminium AM technology in safety-critical components where structural integrity is paramount.

7. TWI's Contribution in Understanding Structural Integrity in AM

Since 2012, TWI has become home to the National Structural Integrity Research Centre (NSIRC), and has delivered >140 PhD students in partnership with University institutions.

The Fatigue and Fracture Integrity Management (FIM) Section has itself undertaken research into the structural integrity of AM considering different processes and materials.

An overview of the research projects (**RPxx**) undertaken is as follows:

RP01: Structural Integrity Assessment of Cold Spray Additive Manufactured Ti-6Al-4V,
Dr Dibakor Boruah

The PhD research [24] investigated Cold Spray (CS), a solid-state AM technique, which has gained significant attention for repairing high-value structural components and providing protective coatings.

The CS technology enables material deposition in the solid-state without high thermal loads. Resulting in deposits with high density, minimal or no oxidation, and no phase transformation or heat-affected zones, while maintaining manageable levels of residual stress.

The work focused on advancing the understanding of residual stresses, microstructure and mechanical properties of CS Ti-6Al-4V deposits. Key areas of study included:

- *Understanding on Residual Stress Mechanisms:*

  Residual stresses in CS Ti-6Al-4V were found to be primarily quenching-dominant, with high tensile stresses near the surface and compressive stresses near the interface. Techniques such as reducing the number of layers, thinning layers (via increased scanning speed), and employing a cross-hatch toolpath effectively minimised these stresses.

- *Adhesion Strength Improvements and Novel Test Development:*

  A novel adhesive-free Collar-Pin Pull-off (CPP) test was introduced, addressing the limitations of the standard ASTM C633 test. Adhesion strength improved significantly under optimised deposition parameters and enhanced substrate preparation. Post-deposition thermal treatments further enhanced adhesion strength, achieving values greater than 770MPa.

- *Improvement of Mechanical Properties through Post-Deposition Thermal Treatments:*

Post-deposition thermal treatments, such as Solution Treatment and Aging (STA), Hot Isostatic Pressing (HIP), and combined HIP+STA, significantly improved mechanical properties. Tensile strength increased from ~290MPa to ~890MPa, and elastic modulus rose from ~81GPa to ~110GPa. However, residual porosities (~1.8% post-HIP) limited further enhancements in elongation and toughness.

- *Evaluation of Laser-Assisted Cold Spray (LACS):*
  The integration of laser assistance into cold spray deposition significantly enhanced interfacial adhesion through complete interfacial mixing and reduced porosity to below 0.4% in the deposited material.

Cold spray, when combined with optimised post-deposition thermal treatments or laser assistance, provides enhanced microstructural quality. This makes it ideal for applications such as:

- Rapid and cost-effective repair of high-value structural components, reducing downtime and material waste.
- Protective coatings with superior adhesion strength, extending component lifespan.
- Additive manufacturing of low-to-medium complexity geometries with improved mechanical properties.

RP02: Structural Integrity of Cold Spray repaired AA7075, Dr Ali Bakir

Components manufactured from AA7075 (a high-strength aluminium alloy extensively used in the aerospace industry) are prone to damage from cyclic loading and corrosion (Figure 6). Due to its sensitivity to temperature and oxidation, conventional repair methods are not suitable for AA7075.

Limited data exist on the mechanical performance of repaired specimens under static and cyclic loading. Additionally, there is a need to standardise repair techniques.

Figure 6 Corrosion damage to AA7075 [25].

Solution heat treatment (SHT) of the powder and substrate pre-heating were performed to understand the effect of hardness on the bonding mechanism. SHT was found to help homogenise the dendritic structure of the as-received powder, as well as increase deposition efficiency, reaching 21% compared to 7% for the as-received powder. Due to the softening of the substrate, the particle penetration was limited leading to a delamination of the coating. However, with substrate pre-heating, the bonding between the powder particle and substrate is improved, which is crucial for the structural integrity (Figures 7 and 8).

A programme of process optimisation and mechanical testing was carried out to understand the performance of the process on AA7075 for repair scenarios [25]. This included heat treatment, tensile testing and fatigue testing, supported by finite element analysis, Figure 9.

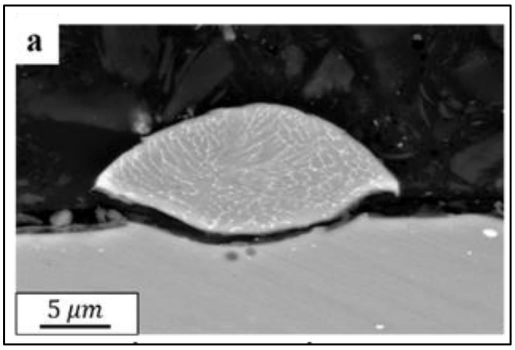


Figure 7 Particle adhesion without SHT [25].

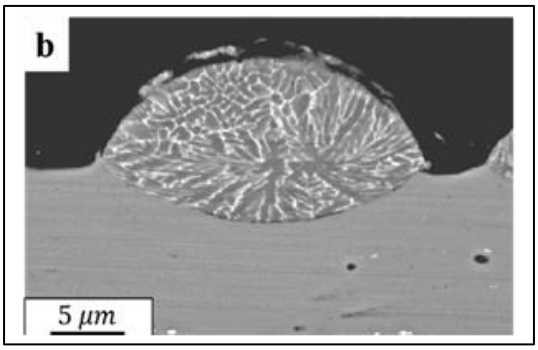


Figure 8 Particle adhesion on pre-heated substrate [25].

The fatigue performance of the CS repair was found to be very promising and demonstrated the capability of the CS repair 'patch' to carry loading_until its failure was proven, Figure 10. Comparison between different repaired geometries and repaired/unrepaired/undamaged specimens were made to show the effectiveness of repair process.

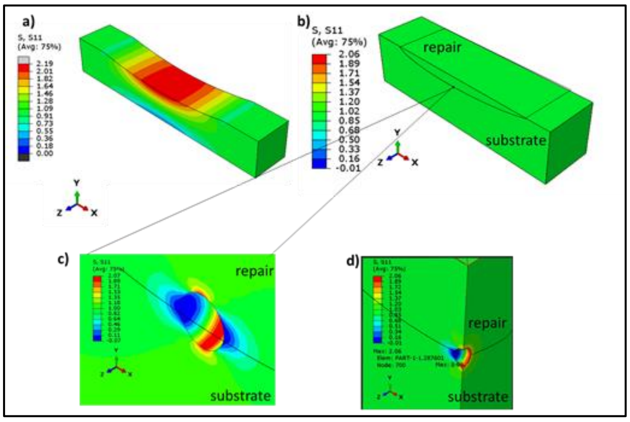


Figure 9 FEA of repaired substrate [25].

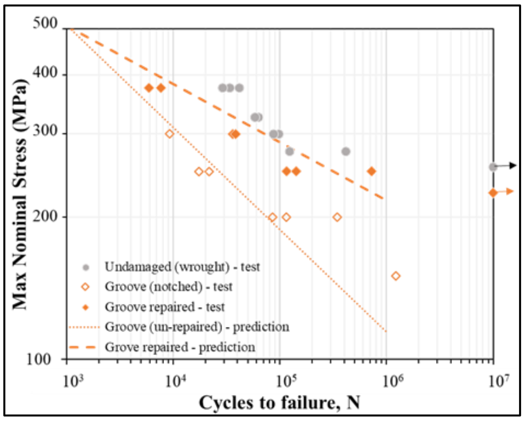


Figure 10 Fatigue performance of CS repair [25].

The work performed concluded that pre- and post-deposition treatments can enhance the mechanical performance of repaired materials. Furthermore, the CS AM repair process was found to improve fatigue performance as compared to damaged, unrepaired specimens

RP03: Structural Integrity Assessment of 316L Stainless Steel Produced by Additive Manufacturing, *Dr Mehran Shariarifar*

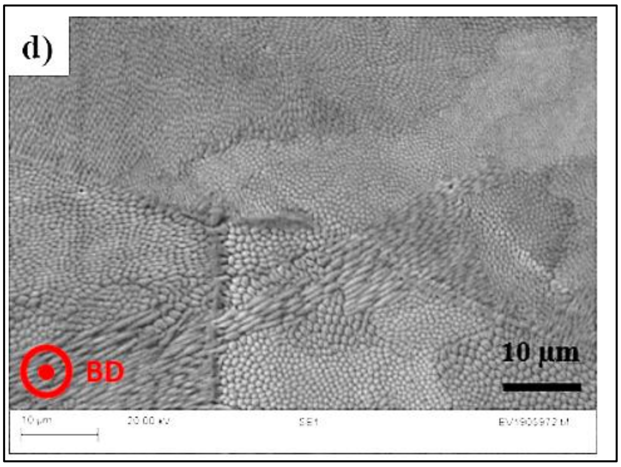
The PhD research [26] aimed to provide an assessment of the structural integrity performance of L-PBF 316L with various post-process heat-treatment conditions. The material chosen has a wide variety of applications in different industrial sectors, making it an attractive material for the L-PBF AM technology.

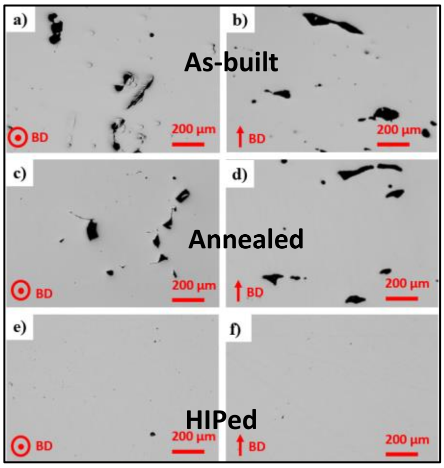
Following thorough review, a general lack of data and understanding on the effect of different post-process heat-treatments on the material performance under static and fatigue loading and the correlation between mechanical properties with microstructure was observed. Moreover, the effect of residual stress and microstructure on fatigue crack growth rate (FCGR) was not fully understood.

Some of the key findings from the study included:

Microstructure evaluation: This revealed that the material in the as-built condition has a fine grain cellular structure (i.e. fine dendritic grains within grains resulting from high cooling rates during AM).

Such fine grain microstructure was not found after annealing and HIPing where a more homogenised microstructure was present, Figure 11.





a) b)

Figure 11 SEM image showing a fine grain cellular structure (a) and micrographs showing a more homogenised microstructure following HIPing (b) [26].

Effect on tensile properties: The as-built samples had higher yield strength, but lower ductility compared to the annealed and HIPed samples.

Fatigue performance in the as-built and HIPed conditions: The as-built horizontal samples exhibited higher fatigue strength than their vertical counterparts, with fatigue crack initiation occurring from lack-of-fusion or rare occurrences of gas pores near the surface in the as-built samples.

Fatigue crack growth rate testing: The material resistance to crack propagation was improved after annealing and HIPing. The crack growth rate in the Paris law regime was found to be 20-50% lower as compared to stress-relieved and as-built samples. The effect on ΔK_{th} was found to be improved by 60% and 75% after annealing and HIPing respectively.

The effect of residual stress: Measurements showed compressive residual stresses in the mid-thickness, balanced by tensile residual stresses near the surface in the as-built condition, for both vertical and horizontal samples. Stress-relieving reduced the residual stresses but did not fully eliminate them. Despite this, no significant difference was observed in the crack growth rate of the two conditions.

In summary, the findings of this research [26] showed that post-process heat-treatments can have significant effects on the microstructure and material properties of L-PBF 316L. A detailed microstructure and defect characteristic was performed to link to mechanical properties. Both annealing and HIPing were found to improve fatigue properties. The almost fully-dense HIPed samples with a high ductility showed higher fatigue strength compared to the as-built samples. In terms of fatigue crack growth rate, the effect of residual stresses was found to be negligible for the single edge notched bend (SENB) configuration that was used in this study. Both annealing and HIPing, however, were found to change the microstructure and improved the resistance of the material to crack growth.

RP04: Influence of porosity on fatigue of additive manufactured titanium alloy Ti-6Al-4V,
Dr Emre Akgun

In this PhD study, the effect of porosity on high-cycle fatigue behaviour under constant amplitude axial loading was investigated for an AM titanium alloy Ti-6Al-4V [27]. Process-induced defects have been identified as one of the principal failure sources in metal AM under cyclic loading; yet, understanding how they impact fatigue behaviour remains open for discussion.

Two different AM processes, namely WAAM and L-PBF, were employed in this research. A targeted experimental programme was developed to concentrate on the influence of defects by circumventing other parameters that might impact the fatigue life such as the surface roughness, build direction and more.

The experimental results were analysed both from a linear elastic fracture mechanics perspective and a total life perspective using the local elastic stresses in the vicinity of a pore. Key findings are summarised below.

Individual fatigue life stages were investigated by following surface cracks initiated from pores using the replica technique. Cracks identified at 'first detection', were less than 50µm in length and occupied roughly 50% of the total fatigue life. This suggests that the crack initiation stage was significant and it should be accounted for in fatigue life prediction approaches; noting that the measurements were limited to surface observations. During the crack propagation stage, small cracks could grow faster than the long crack growth measurements for the same nominal ΔK value, i.e. the so-called small crack behaviour. Such a behaviour was observed near the threshold region; however, it was less significant when compared to conventional manufactured specimens.

The total fatigue life of AM Ti-6Al-4V was found to vary by up to three orders of magnitude for nominally similar test specimens. Defects were considered as one of the causes of the observed scatter, and in this work, defect location (embedded or surface breaking) was found to be the dominant factor rather than defect size. In fact, within a same defect category, such as the surface pores, the scatter of fatigue life (Figure 12) due to the variation in crack initiating defect size was less than a conventional manufactured Ti-6Al-4V, where the scatter assumed to be related to the distribution of unfavourably oriented surface grains.

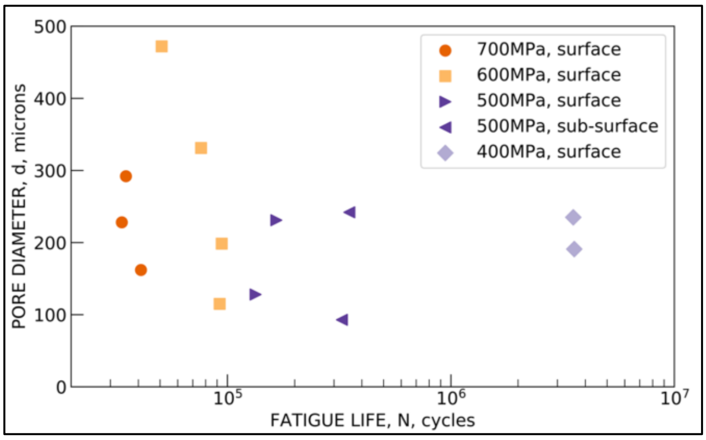


Figure 12 Influence of pore diameter on fatigue life [27].

It was found [27] that the analogy of assuming pores as cracks was lost after a certain transition size and fatigue life reduction saturated despite the increase of crack initiating pore diameter roughly by a factor of four.

RP05: The Effects of Defects on the Fatigue Performance of Selectively Laser Melted AlSi10Mg Alloys, Dr Saad Syed Iqbal Ahmed

Despite its potential, the widespread implementation of Selective Laser Melting (SLM) (Figure 13) has been hindered by limitations in fatigue strength and reliability. This PhD research addressed this critical issue, aiming to enhance the understanding of fatigue behaviour in SLM components, ultimately paving the way for their utilisation in safety-critical applications across various industries including automotive, heat exchangers and aerospace [27].

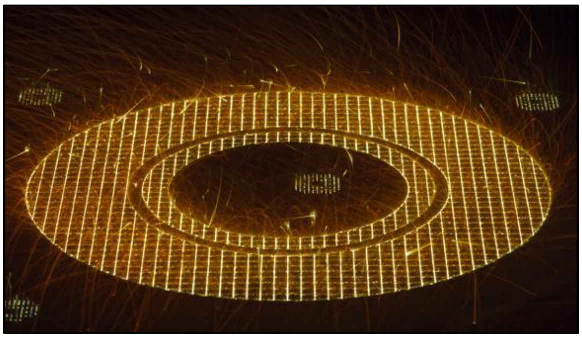


Figure 13 Selective laser melting (courtesy of TWI Ltd).

The work performed included a comprehensive examination of the correlation between defects and the fatigue performance of SLM Al-Si10-Mg alloys using advanced techniques such as X-ray Computed Tomography (X-CT) and microstructure characterisation. This study advances the mechanistic understanding of defect-driven fatigue behaviour in L-PBF AlSi10Mg, ultimately contributing to the improved reliability and performance of these components.

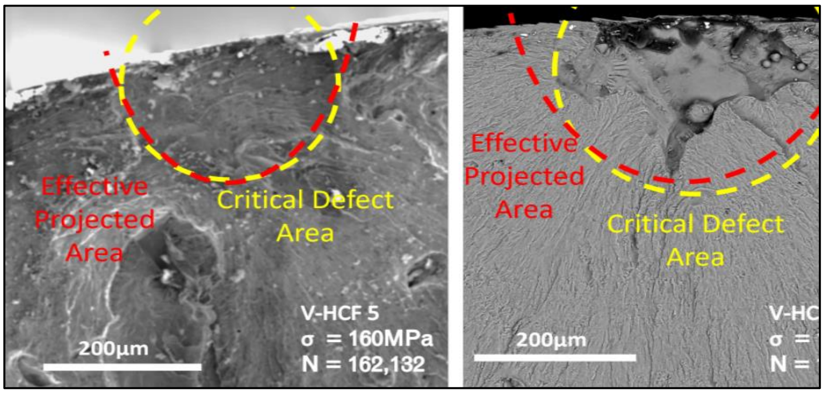


Figure 14 Vertically orientated samples showing presence of critical defects [28].

Through the use of X-CT and CT, both pre- and during (respectively) fatigue testing, and utilising post-mortem electron back scatter detection (EBSD), it was possible to identify defects and observe any associated crack initiation, Figure 14. This along with validated crack growth modelling led to the following findings [28]:

Correlation of Projected Area to Fatigue Properties:
The primary cause of the observed lower fatigue resistance was found to be due to the presence of pancake shaped lack-of-fusion (LOF) defects.

Time Resolved X-ray CT and Single Crack Model:
The fatigue crack propagation behaviour at multiple stages of propagation for a vertical ALSi10Mg component was successfully captured. Using the critical defect size as the primary parameter, the single crack model was used to predict the crack growth front. The model showed very good agreement with the X-CT results, giving an error of ~10%. The crack front predicted by the model was also able to explain discrepancies in the S-N curves.

Model predictions of Fatigue Crack Behaviour:
Small LOF defects that lie edge-on in horizontal samples were observed on fracture surfaces. Thus, the model predicted the horizontal samples to be predominantly initiation dominant, as its defect

morphology made it difficult for a fatigue crack to initiate early. In vertical samples, the presence of large in-plane pancake shaped LOF defects meant that cracks initiated early. The crack propagation lives predicted by the model allowed an understanding as to whether the fatigue life was initiation or propagation dominant.

Fatigue Crack Behaviour of Horizontal Samples:
Critical defects were also located in regions of fine microstructure, with cracks initiating at the ends of edge-on LOF defects. In the area of crack initiation, intergranular crack growth along the grain boundaries of fine equiaxed grains was observed. Whereas, within the fatigue crack propagation region, transgranular crack growth was mainly observed, even as the crack approached the fast fracture zone. This was found to be the dominant mode of crack growth observed across the fracture surface of horizontal samples.

Sub-critical Crack Behaviour:
Sub-critical defects were found to propagate in a mixed mode of transgranular and intergranular growth, dependent on the local microstructure around the defect. Crack growth from these defects, in the short crack regime, was dominated by transgranular growth. Towards the end of the short crack region, the crack growth mode switched to intergranular; due to the influence of the plastic zone diminishing outside the short crack region.

RP05: Effects of Ti-6Al-4V powder recycling in electron and laser beam powder bed fusion additive manufacturing, Dr Gowtham Soundarapandiyan

This PhD research aimed to highlight the different types and mechanisms of Ti-6Al-4V powder degradation, as a consequence of powder recycling, and its subsequent impact on the build properties [29]. Whilst recycling of unused surplus powder after LB-PBF and EB-PBF processes, improves process efficiency, some of the recycled powder particles may have different physical and chemical characteristics due to degradation during part manufacturing, recovery, powder handling, and reuse that can affect the quality of the build parts. Therefore, it is important to understand the properties of the recycled powder, especially when it is used for manufacturing safety critical parts for aerospace applications.

Typically, in industry, recycled powder is often blended or topped-up with virgin powder during recycling to maintain the build volume. The different physical and chemical properties in the recycled powder as compared to the virgin powder (Figure 15) may cause localised inhomogeneity in the build properties.

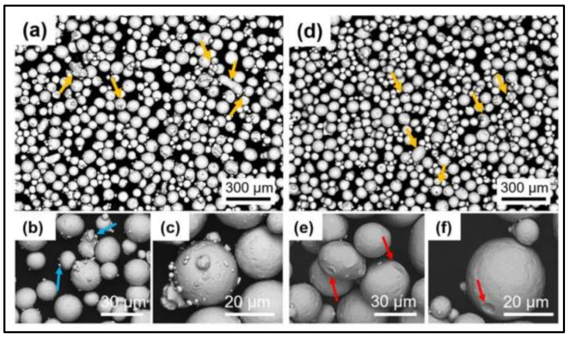


Figure 15 SEM images of virgin (a-c) and recycled (d-f) powders [29].

The research was split into two parts:

- Part 1: An evaluation on the evolution of powder properties for up to 10 build cycles, using a simulated powder recycling strategy that enabled minimal virgin powder top-up in EB-PBF process.
- Part 2: An investigation of the effects of blending a high and low oxygen content Ti-6Al-4V powder on the build properties using in-situ and ex-situ experiments in the LB-PBF process.

The main findings from Part 1 were:

- A heterogeneous powder degradation, with the powder particles located near the melt zone suffering maximum degradation.
- Degradation in the powders physical characteristics was found to cause an increase in the number of lack-of-fusion defects in the specimens produced from the recycled powder. However, post-thermal treatment processes, hot isostatic pressing (HIPing) + solution treatment + ageing appears to be promising in eliminating the lack-of- fusion defects in the recycled builds.
- An increase in the oxygen content was unavoidable due to the reactive nature of the alloy, therefore, the recycled powder showed an 0.02wt.% increase in oxygen content compared to the virgin powder. However, since the measured content in the recycled powder was within the maximum limit (0.13wt.%), only a slight increase in the material yield and tensile strength with negligible changes in ductility were observed.

The main findings from Part 2 were:

- Following the implementation of increased oxygen content (0.12wt.%, and 0.40wt.%.), the high oxygen content powder particles had a positive effect in reducing the number of melt ejections, surface roughness and defect population in the build parts.

A programme of mechanical (Charpy impact, tensile, hardness and high cycle fatigue) tests and metallurgical analysis (microstructure and defect distribution) were subsequently performed to investigate the impact of powder recycling on build properties.

The research performed [29] showed that the changes in the Ti-6Al-4V powder physical properties following reuse are small, and the impact on built properties, such as the increase in lack-of-fusion defects in the builds produced from recycled powder, can be eliminated by employing additional post-thermal treatments.

8. Standards Development and Future Research Directions

The development of comprehensive Standards for AM components represents a crucial dimension of current research efforts, particularly as these technologies transition from experimental to production applications. The approach to specifying AM aluminium parts currently follows guidance from ASTM and ISO Standards [4-6], though this remains more complex than for conventionally manufactured components due to the numerous process parameters that influence final properties [3]. The integration of these Standards into industrial practice continues to evolve as research provides more comprehensive understanding of process-structure-property relationships in AM components, gradually building the foundation for more streamlined qualification protocols.

Future research directions will likely focus on several key areas to advance structural integrity understanding and assurance for AM components:

- Expanded testing under diverse environmental conditions will provide more comprehensive performance profiles, addressing the current limitations in long-term reliability data that hamper industrial adoption [2] [10] [30-31].
- Development of in-situ monitoring and real-time quality control methods promises to improve manufacturing consistency, potentially enabling immediate AI driven identification and correction of defects during production [7] [10] [32].
- Advanced simulation capabilities that accurately predict the relationship between process parameters and resulting material properties will accelerate process optimization and component design, reducing the current reliance on extensive empirical testing [10].
- Advanced alloys such as tailored aluminium alloys e.g. AD1 and steel composites with improved AM compatibility [1] [11].
- Development of ASTM/ISO Standards for aluminium AM to streamline certification [11] [32].

The trajectory of current research suggests increasing specialisation toward industry-specific applications and requirements. Studies examining corrosion-fatigue performance of WAAM steel components for marine environments exemplify this targeted approach, acknowledging that performance requirements vary significantly across operational contexts [2]. Similar application-specific research programs focusing on aerospace, automotive, energy production, and medical applications will likely emerge to address the unique challenges each sector presents. This specialisation allows more nuanced understanding of how AM components perform under industry-relevant conditions, accelerating appropriate technology adoption while ensuring adequate safety margins.

TWI's FIM Section is committed to the understanding of structural integrity related matters in AM and is launching two Joint Industry Projects (JIPs):

- **Structural Integrity of Additive Manufactured Materials** - *Dr Mehran Shariarifar, Senior Engineer*
  Investigating the fatigue and fracture performance of AM steel, copper, nickel and titanium alloys.
- **Structural Integrity of Additive Manufactured Materials for Aerospace Applications** –
  Dr Mehran Shariarifar, Senior Engineer
  A structural integrity assessment of stainless, titanium and nickel based super alloys produced via additive manufacturing (WAAM and DED), focusing on the fatigue and fracture performance in air and high temperature applications.

For further information on these JIP's please email: contactus@twi.co.uk

9. Conclusions

The current status of research regarding structural integrity of AM parts in steels and aluminium alloys reflects a field making substantial progress while still addressing significant challenges. Comprehensive studies have characterized how manufacturing processes like WAAM for steels and powder bed fusion for aluminium alloys influence material properties and component performance, providing crucial data to support industrial implementation. This research has expanded beyond basic mechanical property assessment to include application-specific performance characteristics such as corrosion resistance, fatigue behaviour, and fracture toughness, reflecting the maturing nature of the field.

Despite the significant progress made, the main challenges in producing any additive structures is in the amount of flaws that are present as compared to a wrought product. Therefore, the standardisation of procedures for qualification of AM processes, giving clear acceptance criteria, and non-destructive testing techniques, which are calibrated for these type of flaws, will be very important for its widespread adoption.

The development of aluminium-specific standards for additive manufacturing processes represents a particular gap in the current landscape, though efforts by organisations like ASTM continue to advance the regulatory framework. Recent innovations in alloy development specifically optimized for additive processes, such as Addalloy® 5T (AD1) for aluminium applications, demonstrate the potential for continued performance improvements through material engineering approaches.

Looking forward, the research landscape will likely evolve toward more application-specific characterisation, expanded testing under diverse environmental conditions, and development of advanced in-process monitoring techniques. These directions will address current knowledge gaps while enhancing confidence in the long-term reliability of additively manufactured components. As understanding of process-structure-property relationships continues to advance, AM of steel and aluminium components will increasingly transition from specialized applications to mainstream production, revolutionizing manufacturing approaches across multiple industries while maintaining essential structural integrity requirements.

10. References

1. (https://3dprintingindustry.com/news/u-s-research-delves-deeper-into-the-structural-integrity-of-3d-printed-aluminum-parts-196435/)
2. Ermakova, A. (2023): Structural integrity assessment of wire are additively manufactured low carbon steel components for marine applications. PhD Thesis. University of Strathclyde, Glasgow.
3. (https://www.protomatic.com/how-to-specify-additively-manufactured-aluminum-parts)
4. ISO/ASTM 52911-2:2019, Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers.
5. ASTM F2924-14, Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion.
6. ASTM F3055-14a, Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion.
7. (https://thetandt.com/additive-manufacturing-part-inspection/)
8. (https://thetandt.com/additive-manufacturing-flaw-types/)
9. Leirmoa, J. L., & Baturynskaa, I. (2019). Challenges and proposed solutions for aluminium in laser powder bed fusion. 53rd CIRP Conference on Manufacturing Systems.
10. Chen, B. (2024). From lab to industry: How additive manufacturing is transforming structural integrity.(https://www.azom.com/article.aspx?ArticleID=24101)
11. Martucci, A., Aversa, A., & Lombardi, M. (2023). Ongoing Challenges of Laser-Based Powder Bed Fusion Processing of Al Alloys and Potential Solutions from the Literature-A Review. Materials 2023 Jan 26;16(3):1084.
12. Sha, A., Aliyev, R., Zeidler, H., & Krinke, S. (2023). A Review of the Recent Developments and Challenges in Wire Arc Additive Manufacturing (WAAM) Process. J. Manuf. Mater. Process. 2023, 7(3), 97.
13. Zhang, J., Wang, X., Paddea, S., & Zhang, X. (2016). Fatigue crack propagation behaviour in wire+arc additive manufactured Ti-6Al-4V: Effects of microstructure and residual stress. Materials & Design, 90, 551-561.

14. Md Faysal Khan, P.D. Nezhadfar, Paul R. Gradl, Donald Godfrey, Jacky Diemann, Shuai Shao, Nima Shamsaei. (2021). Investigate the height dependency of the micro-/defect-structure and mechanical properties of additively manufactured AlF357 aluminum alloy. Solid Freeform Fabrication 2022: Proceedings of the 33rd Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference. July 25-27. Texas, USA.

15. P.D. Nezhadfar, Spencer Thompson, Ankit Saharan, Nam Phan, Nima Shamsaei. (2021). Structural integrity of additively manufactured aluminum alloys: Effects of build orientation on microstructure, porosity, and fatigue behaviour. Additive Manufacturing 47.

16. Yang, H., Sha, J., Zhao, D., He, F., Ma, Z., He, C., Shi, C., and Zhao, N. (2023). Defects control of aluminum alloys and their composites fabricated via laser powder bed fusion: A review. Journal of Materials Processing Tech. 319.

17. Takata, N., Kodaira, H., Sekizawa, K., Suzuki, A., & Kobashi, M. (2017). Change in microstructure of selectively laser melted AlSi10Mg alloy with heat treatments. Materials Science and Engineering: A, 704, 218-228.

18. Aboulkhair, N. T., Everitt, N. M., Ashcroft, I., & Tuck, C. (2014). Reducing porosity in AlSi10Mg parts processed by selective laser melting. Additive Manufacturing, 1, 77-86.

19. Yang, K. V., Rometsch, P., Jarvis, T., Rao, J., Cao, S., Davies, C., & Wu, X. (2018). Porosity formation mechanisms and fatigue response in Al-Si-Mg alloys made by selective laser melting. Materials Science and Engineering: A, 712, 166-174.

20. Gordon, J., Hochhalter, J., Haden, C., & Harlow, D. G. (2019). Enhancement in fatigue performance of metastable austenitic stainless steel through directed energy deposition additive manufacturing. Materials & Design, 168, 107630.

21. (https://www.3dnatives.com/en/a-complete-guide-to-aluminum-3d-printing-131220234/)

22. Tobias Hauser, Raven T. Reisch, Philipp P. Breese, Yogesh Nalam, Kaivalya S. Joshi, Katharina Bela, Tobias Kamps, Joerg Volpp and Alexander F.H. Kaplan. (2021). Oxidation in wire arc additive manufacturing of aluminium alloys. Additive Manufacturing 41.

23. Martin, J. H., Yahata, B. D., Hundley, J. M., Mayer, J. A., Schaedler, T. A., & Pollock, T. M. (2017). 3D printing of high-strength aluminium alloys. Nature, 549(7672), 365-369.

24. Boruah, D. (2020). Structural integrity assessment of cold spray additive manufactured titanium alloy Ti-6-Al-4V. PhD thesis, Coventry University.

25. Bakir, A. (2025). Structural Integrity Assessment of Cold Spray Repaired Aluminium Alloy 7075 Specimens. PhD thesis [Final submission], Coventry University.

26. Shariarifar, M. (2023). Structural integrity assessment of 316L stainless steel produced by additive manufacturing. PhD thesis, Coventry University.

27. Akgun, E. (2023). Influence of porosity on fatigue of additive manufactured titanium alloy Ti-6-Al-4V. PhD thesis, Coventry University.

28. Ahmed, S. (2024). The effects of defects on the fatigue performance of laser powder bed fusion AlSi10Mg alloys. PhD thesis. University of Manchester.

29. Soundarapandiyan, G. (2021). Effects of Ti6Al4V powder recycling in electron and laser beam powder bed fusion additive manufacturing. PhD thesis, Coventry University.

30. Alexandreanu, B., Zhang, X., Chen, Y., Chen, W-Y. & Li, M. (2022). Mechanical testing of additively manufactured materials. Nuclear science and engineering division, Argonne National Laboratory. Doc No. ANL/NSE-22/83.

31. Liu, L., Wang, S., Li, G. & Ma, Y. (2024). Microstructure study on very high cycle fatigue of and additively manufactured aluminium alloy via advanced characterization methods. Applied Sciences. 2024. 14. 2025.

32. Paletti, L. & Amsterdam, E. (2019). Impact of additive manufacturing on structural integrity methodologies for aerospace components. NLR – Royal Netherlands Aerospace Centre. Doc No. NLR-TP-2019-368.