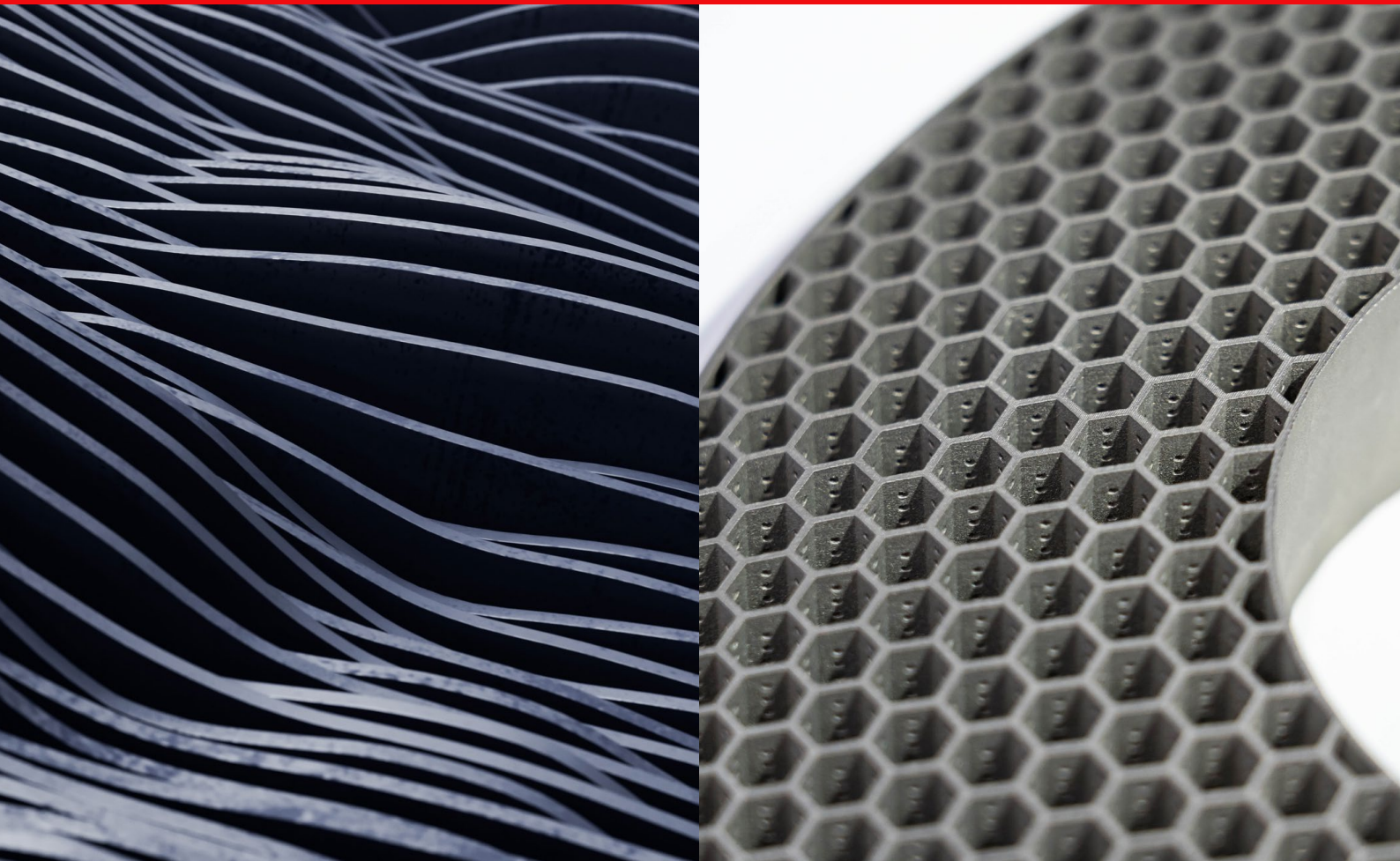


PAS 6011:2020

Additive manufacturing – Non-destructive testing for use in directed energy deposition – Guide



**UK Research
and Innovation**

**NATIONAL
CENTRE
ADDITIVE
MANUFACTURING**



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Foreword

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Relationship with other publications

PAS 6010, *Additive manufacturing – Wire for directed energy deposition (DED) processes in additive manufacturing – Specification*

PAS 6012, *Additive manufacturing – Wire arc – Guide*

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As a guide, this PAS takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice.

Presentational conventions

The guidance in this PAS is presented in roman (i.e. upright) type. Any recommendations are expressed in sentences in which the principal auxiliary verb is “should”.

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Where words have alternative spellings, the preferred spelling of the Shorter Oxford English Dictionary is used (e.g. “organization” rather than “organisation”).

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Introduction

Directed energy deposition (DED) is an additive manufacturing (AM) process, which focuses a thermal energy source to melt and fuse deposited materials. It is one of the seven main AM methods (ASTM/ISO 52900) and represents with powder bed fusion (PBF) one of the two main commercial processes for metal additive manufacture (MAM).

DED was one of the first AM processes, originating from the use of welding equipment in the 1960s to produce three-dimensional welding, and became part of AM in the 1990s. Despite its long history, DED is not as well-known as many other AM processes. It was extensively developed for military equipment and consequently received little publicity.

However, it is gaining greater commercial interest as it has a number of advantages over other processes. Particularly, DED can be:

- attached to a multi-axis manipulator, which adds material at almost any angle and does not require a build chamber;
- used to repair or upgrade existing parts, remodel or replace corroded areas; and
- applied to very large structures.

The term DED covers a range of commercial terminologies and implementations, all of which deposit and melt a feedstock material on a build substrate where it solidifies.

However, while DED methods are commercially attractive due to the lower costs in comparison with other AM processes, there is a lack of knowledge of the mechanical and lifetime performances of the parts produced by DED.

Traditional manufacturing processes are well defined and understood, but the increased complexity of AM processes leads to poor understanding. The relationship between process, geometry and microstructure of AM parts and the absence of predictive models make it difficult to validate the quality and integrity of the build. Accordingly, guaranteeing part mechanical performance is difficult. This gap in the assurance of the quality of AM parts is a key technological barrier that prevents the widespread adoption of AM technologies.

AM is especially attractive for industries, such as aerospace, with large, low volume, high-value parts in safety-critical applications. In these industries, the need for qualification and certification for requirements could not be greater. Therefore, in the absence of fully understood processes, the use of AM parts in such critical applications requires that parts are qualified by a detailed inspection.

While industry is pushing for in-situ methods, there is a lack of in-situ monitoring capability. Current in-situ methods are only suitable for part surface defects while real-time monitoring has not been adequately demonstrated for DED.

In the short to medium term, non-destructive testing (NDT) has been repeatedly identified as critical to the success of additive manufacture by providing a means of validating the quality of the build and to gather data to increase knowledge and understanding.

Therefore, this PAS focuses on the determination of the part quality through the use of NDT. It examines traditional, new and emerging techniques, identifying their suitability for use with DED. Geometric control and in-process sensing are not part of this document.

It makes recommendations for points in the process where specific NDT methods may be applied. The optimal points in the process for use of NDT include between deposition of layers and (intra-layer), after the build process (post-build), and if necessary in post-processing (finished/post process).

A subgroup of emerging NDT techniques which may have the greatest potential for future DED application is highlighted in Clause 11, with the aim that industry adopt and accelerate their development.

1 Scope

This PAS provides guidance on non-destructive testing (NDT) for use in directed energy deposition (DED) additive manufacturing (AM) processes and covers:

- typical causes and the nature of defects;
- review of other potentially relevant standards (welding);
- review of NDT methods' capability for DED AM;
- emerging NDT with potential for DED AM; and
- shortlist NDT methods with potential for validation trials.

This PAS is relevant to users who wish to identify suitable methods for the inspection of parts manufactured using a DED AM process.

This PAS is of interest to regulatory bodies, material suppliers, certification bodies, inspectors, and researchers.

This PAS does not cover NDT during DED AM builds and NDT trials, or other AM processes.

This PAS does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes provisions of this PAS. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ASTM F3049, *Standard guide for characterizing properties of metal powders used for additive manufacturing processes*

ASTM F3187, *Standard guide for directed energy deposition of metals*

ASTM/ISO 52900, *Standard terminology for additive manufacturing – General principles – Terminology*

BS EN 1330-1, *Non-destructive testing – Terminology – Part 1: List of general terms*

BS EN 1330-2, *Non-destructive testing – Terminology – Part 2: Terms common to the non-destructive testing methods*

BS EN 1779, *Non-destructive testing – Leak testing – Criteria for method and technique selection*

BS EN 13018, *Non-destructive testing – Visual testing – General principles*

BS EN 13068-1, *Non-destructive testing – Radioscopic testing – Quantitative measurement of imaging properties*

BS EN 13068-3, *Non-destructive testing – Radioscopic testing – General principles of radioscopic testing of metallic materials by X- and gamma rays*

BS EN 13554, *Non-destructive testing – Acoustic emission testing – General principles*

BS EN ISO 3452-1, *Non-destructive testing – Penetrant testing – Part 1: General principles*

BS EN ISO 5579, *Non-destructive testing – Radiographic testing of metallic materials using film and X- or gamma rays – Basic rules*

BS EN ISO 9934-1, Non-destructive testing – Magnetic particle testing – Part 1: General principles

BS EN ISO 10863, Non-destructive testing of welds – Ultrasonic testing – Use of time-of-flight diffraction technique (TOFD)

BS EN ISO 13588, Non-destructive testing of welds — Ultrasonic testing — Use of automated phased array technology

BS EN ISO 15549, Non-destructive testing – Eddy current testing – General principles

BS EN ISO 16810, Non-destructive testing – Ultrasonic testing – General principles

ISO/ASTM 52910, Additive manufacturing – Design – Requirements, guidelines and recommendations

ISO/TS 18173:2005, Non-destructive testing – General terms and definitions

PD CEN/TR 14748, Non-destructive testing – Methodology for qualification of non-destructive tests

3 Terms, definitions and abbreviations

For the purposes of this guide, the terms and definitions given in ASTM/ISO 52900, BS EN 1330-1, BS EN 1330-2, and the following apply.

3.1 Terms and definitions

3.1.1 additive manufacturing (AM)

process of joining materials to make parts from three-dimensional model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies

3.1.2 defect

one or more flaws whose aggregate size, shape, orientation, location or properties do not meet specified acceptance criteria and are rejectable

[SOURCE: ISO/TS 18173:2005 2.6]

3.1.3 directed energy deposition (DED)

additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited

[SOURCE: ISO/TS 18173:2005 2.9]

3.1.4 discontinuity

lack of continuity or cohesion by way of an intentional or unintentional interruption in the physical structure or configuration of a material or component

3.1.5 flaw

imperfection or discontinuity that may be detectable by NDT and is not necessarily rejectable

[SOURCE: ISO/TS 18173:2005 2.11]

3.1.6 imperfection

departure of a quality characteristic from its intended condition

[SOURCE: ISO/TS 18173:2005 2.13]

3.1.7 macro

scale of features with linear dimensions greater than several millimetres

3.1.8 meso

scale of features with linear dimensions from sub-millimeter to several millimetres

3.1.9 micro

scale of features with linear dimensions less than one millimetre

3.1.10 NDT method

discipline applying a physical principle in non-destructive testing

[SOURCE: BS EN ISO 9712:2012 3.17]

3.1.11 NDT technique

specific way of utilizing an NDT method

[SOURCE: BS EN ISO 9712:2012 3.19]

3.1.12 non-destructive evaluation

see non-destructive testing (3.1.14)

[SOURCE: ISO/TS 18173:2005 2.17]

3.1.13 non-destructive inspection

see non-destructive testing (3.1.14)

[SOURCE: BS EN ISO 9712:2012 3.19]

3.1.14 non-destructive testing (NDT)

development and application of technical methods to examine materials or components in ways that do not impair their future usefulness and serviceability, in order to detect, locate, measure and evaluate flaws, to assess integrity, properties and composition, and to measure geometrical characteristics

[SOURCE: ISO/TS 18173:2005 2.20]

NOTE In this guide, the term *non-destructive testing* is used rather than *NDE* or *NDI* as defined by ISO/TS 18173:2005.

3.1.15 part

joined material forming a functional element that could constitute all or a section of an intended product

3.2 Abbreviations

AC	alternating current	MAM	metal additive manufacturing
ACPD	alternating current potential drop	MPT	magnetic particle testing
AE	acoustic emission	NDE	non-destructive evaluation
AM	additive manufacturing	NDI	non-destructive inspection
ASTM	American Society for Testing and Materials	NDT	non-destructive testing
CAD	computer aided design	Nd:YAG	neodymium-doped yttrium aluminium garnet
CNC	computer numeric control	PAUT	phased array ultrasonic testing
DC	direct current	PAW	plasma arc welding
DCPD	direct current potential drop	PBF	powder bed fusion
DED	directed energy deposition	PCRT	process compensated resonance testing
DI	digital imaging	PD	potential drop
EBF	electron beam freeform fabrication	PT	penetrant testing
EBM	electron beam melt	PTA	plasma transferred arc
EC	eddy currents	QC	quality control
ET	eddy current testing	QWHE	quantum well hall effect
ECCT	eddy current thermography	RT	radiographic testing
EM	electro-magnetic	SLM	selective laser melting
EMAT	electro-magnetic acoustic testing	SQUID	superconducting quantum interference device
GMA	gas metal arc	UT	ultrasonic testing
GTA	gas tungsten arc	VI	visual inspection
GMAM	gas metal arc welding	VTT	vibro-thermography
GTAW	gas tungsten arc welding	WAAM	wire-feed arc additive manufacturing
HIP	hot isostatic pressing	WFAM	wire-feed additive manufacturing
IR	infrared	WLAM	wire and laser additive manufacturing
LOF	lack of fusion	XBT	X-ray backscatter technology
LTT	laser thermography	XCT	X-ray computed tomography
LUT	laser ultrasonic testing		

4 Significance and use

4.1 Directed energy deposition (DED) is an additive manufacturing (AM) process, which focuses a thermal energy source to melt and fuse deposited materials. It is one of the seven main AM methods as described in ASTM/ISO 52900 and represents, with powder bed fusion (PBF), one of the two main commercial processes for metal additive manufacture (MAM). The DED process is described in ASTM F3187.

4.2 Traditional manufacturing processes are well defined and understood. However, the increased complexity of AM processes leads to poor understanding of the relationship between process and quality. These include geometry and microstructure of AM parts, the absence of predictive models causing difficulties in the quality and integrity of the build. Accordingly, guaranteeing part mechanical performance is difficult. This gap in the quality assurance of AM parts is a key technological barrier that prevents the widespread adoption of AM technologies.

4.3 For safety-critical applications in industries such as aerospace, the need for qualification and certification for requirements could not be greater. Therefore, in the absence of fully understood processes, the use of AM parts in such critical applications requires that parts are qualified by a detailed inspection.

4.4 While industry is pushing for in-process methods, there is a lack of in-process monitoring capability. Current in-situ methods are only suitable for part surface defects while real-time monitoring has not been adequately demonstrated for DED.

4.5 In the short to medium term, NDT has been repeatedly identified as critical to the success of additive manufacture by providing a means of validating the quality of the build and to gather data to increase knowledge and understanding.

5 DED need and impediments to adoption

5.1 General

5.1.1 DED is a complex multi-stage process with the potential for wide variability in final part properties. The wide range of defect types, lack of mature defect impact data for AM parts and the absence of predictive models make it difficult to validate the quality and integrity of the build. Guaranteeing part mechanical performance is an impediment to widespread use. Therefore, inspection of parts to assure quality is required and this makes part acceptance using NDT critical to the success of AM.

5.1.2 There is a lack of suitable methods for measurement and a resultant lack of data on quality control parameters for mechanical strength of DED-produced parts, meaning there remains a gap, which can only be filled by measurements.

5.2 DED manufacturing process

5.2.1 The DED process has several stages; each of which has multiple inputs and control parameters and potential to characterize and manage the part quality. At each stage the level of part quality assurance should be taken into account. Successful implementation of a part should begin by considering NDT inspection during the creation of the three-dimensional CAD model of the design. Assurance of part quality should proceed in parallel with characterizing the output at each process stage, from the input material state, the build process iteration, through to the final part.

5.2.2 Process characterization steps are illustrated in Figure 1 and are outlined in 5.2.2.1 to 5.2.2.7.

5.2.2.1 CAD model development and adjustment for DED

At an early stage, the method of manufacture should be identified based on the part specification and cost targets. The 3D structural model should be confirmed as suitable for the manufacturing process. Any additional manufacturing-specific features and support structures should be incorporated as adjustments to the model.

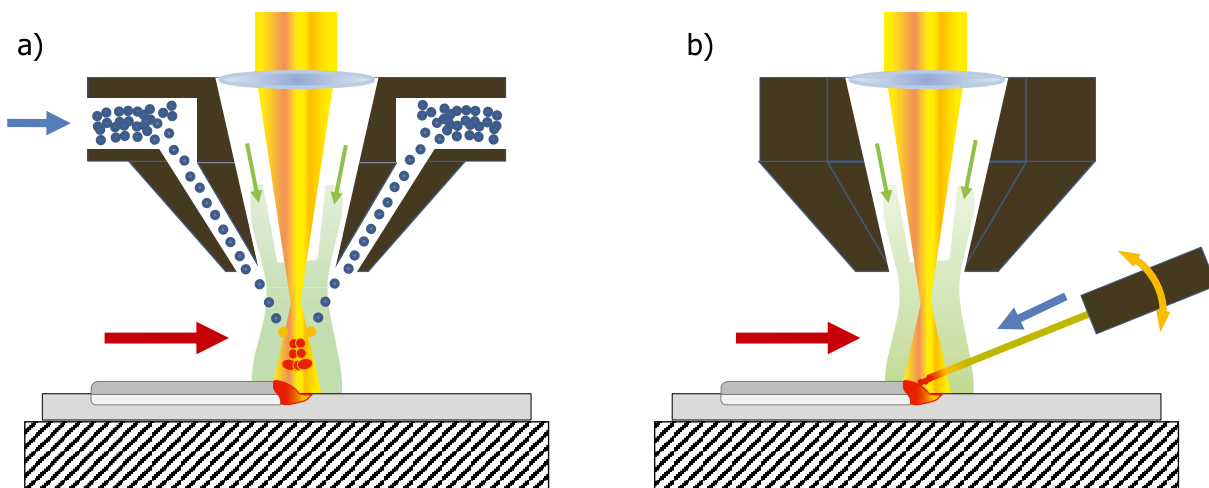
5.2.2.2 Determination of confidence levels for level of part testing

The degree of testing required for each part should be defined based on specific application, or industry requirements. Aerospace, automotive and other industries with low-volume high-value or high-volume safety-critical requirements may require testing of every part or every layer. However, other industries may only require testing of sample parts or inspection of critical areas.

5.2.2.3 Input material manufacture and characterization

The input material quality, physical and functional properties should be confirmed as meeting the specification.

Figure 1 – a) the powder and b) wire DED process head



5.2.2.4 Part certification and qualification

Prototype parts may be produced to establish a parameter set for a material, or confirm the input parameters for the part and the process parameters. This requires that the build process is completed, and the mechanical performance tested and correlated with the in-process measurements.

5.2.2.5 Build process with in-process monitoring

During the build process, measurements can be made for each layer of the structure. At each inspection, macro scale defects should be evaluated to ensure the build remains within specification, while meso and micro scale defects should be monitored to identify process performance trends.

5.2.2.6 Post-build inspection and processing

At the completion of the part build process, an additional full structure NDT should occur to confirm integrity of the part. This should be used to determine the cost effectiveness of the complete part. Post-processing may require surface finishing or whole-part processing, such as HIP to remove or reduce micro scale faults.

5.2.2.7 Post-processing inspection and part release

Performance of post-processing may be required on raw parts from the build. Post-processed parts should be re-tested to confirm performance, determine if post-processing has improved the part and record the final state. The part can then be released to the standard QC and production controls. NDT data from the build should be stored for future reference.

5.3 AM part inspection process

5.3.1 General

5.3.1.1 Industry preference is for in-situ inspection; in concept, this can potentially yield information regarding structure and defects throughout the build process, but it is not without its difficulties, including cleanliness of the working environment, access to part in-process, chemical contamination (oxidization) and interference (electrical and mechanical) from the process.

5.3.1.2 Hence, NDT methods should be the first step in providing process QC and improving process knowledge since the key to process qualification is process knowledge and understanding.

5.3.2 In-process sensing

5.3.2.1 In-situ inspection of parts in DED processes has been demonstrated in research facilities, but adoption has been limited.

5.3.2.2 Typical sensors used include process control parameter logging, optical weld cameras, infrared (IR) imaging, pyrometers and, in some cases, laser scanning. The outputs of these are used to control the process parameters, including source energy, wire feed rate, head scan speed, temperature of the build and gas flow rate. Imaging provides information on the bead geometry and build quality. IR imaging enables monitoring of the melt pool position, diameter and temperature.

5.3.2.3 While in-process monitoring capability for DED has great potential, advanced methods for subsurface characterization have yet to be integrated. Currently, implementation is limited by the data acquisition rate limitations, high data volume, poor spatial resolution and limited field of view issues. Current in-situ methods are based on imaging of the part surface applications. They simplify the problem to melt pool and geometrical signatures using optical and thermal imaging, but visual and thermal methods are a compromise between resolution and field of view, especially for large parts such as those produced by DED.

5.3.2.4 NDT testing of internal geometry, structure and part integrity for defects should be performed using the appropriate test methods as described in Clause 9.

5.3.4 Dimensional tests on part geometry

5.3.4.1 Geometric abnormalities – for example, sagging, deformation and distortion – could be caused by processing issues such as too high a temperature or cooling too fast and may be the product of other defects. Part geometry should be tested in large or complex structures and in materials with known problems. NDT methods can be used to test inner dimensions, but typical methods of testing dimensions include optical or mechanical coordinate measuring machines (CMM) (see BS EN ISO 10675-1).

5.3.4.2 The high throughput of products needed for serial production requires in-process monitoring in parallel with the processing. However, conventional NDT tools are not suitable for in-situ characterization of even simple structures, while the ex-situ characterization of near-net shape parts is challenging for advanced methods.