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Wire and arc additive manufacturing technology – a research perspective

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Overview

Wire and arc additive manufacturing (WAAM) technology consists of a combination of an electric arc as heat source and wire as feedstock. It currently uses off-the-shelf welding equipment, such as welding power source, welding torch and wire-feeding system, while motion is provided by either a robotic arm or computer numerical-controlled gantries. Such a flexible building setup allows for the realisation of elements without theoretical dimensional constraints. Thus, it appears more suitable for structural engineering applications, for which the outputs requested are of the order of several metres (typically 3–5 m long).

WAAM's layer height is commonly in the range of 1–2 mm, resulting in an expected surface roughness of about 0.5 mm for single track deposits. As a result, this is not considered a net shape process, as machining is required to finish the part, and is therefore better suited for low to medium-complexity and medium to large-scale elements, such as those used in structural engineering (Haden *et al.*, 2017; Ji *et al.*, 2017; Uziel, 2016; Williams *et al.*, 2016). Indeed, to obtain pieces of large dimensions, higher printing velocities are required, resulting in larger geometrical imperfections with respect to the digital model. Therefore, much effort is needed for a proper assessment of both the geometrical and mechanical characterisation of the outputs from the WAAM process.

To date, there has been a limited amount of research work concerning the influence of WAAM process parameters on the material properties (Dinovitzer *et al.*, 2019; Kim *et al.*, 2003). For WAAM-processed stainless steels, the available literature reports limited data for maraging steel (Xu *et al.*, 2018), 2Cr13 martensitic stainless steel (Ge *et al.*, 2018), 316L and 304 L austenitic stainless steels (Gardner *et al.*, 2019; Gordon *et al.*, 2018; Haden *et al.*, 2017; Ji *et al.*, 2017; Kyvelou *et al.*, 2020), as well as 2209 duplex stainless steel (Hejripour *et al.*, 2019). The presented results are focused on assessment of the influence of orientation with respect to the deposition layer on the tensile strength (yielding and ultimate tensile

strengths) of WAAM metallic specimens, hence confirming the interest in studying the anisotropy of the printed outcomes. The work by Gordon and co-authors (Gordon *et al.*, 2018) reports Young's modulus values, indicating values around 130–140 GPa, significantly lower than the one registered by the conventional wrought material (about 190 GPa). Wu and co-workers (Wu *et al.*, 2019) found a first correlation between tensile strength and specimen orientation, in terms of grain growth orientation.

The first full-size pedestrian bridge realised with metal 3D printing was designed by MX3D (MX3D, 2023a) and presented at the Dutch Design Week 2018 in Eindhoven (Figure 4.1). The bridge has now been installed in Amsterdam city centre and was opened in 2021.

MX3D, in partnership with engineers from Arup and researchers from Imperial College London, Delft University of Technology (TU Delft) and the University of Bologna, designed, modelled, built and tested the bridge, which has a width of 2.5 m and a span of 10 m. The structure was printed using WAAM directed energy deposition (DED) using stainless steel wire.

<Insert Figure 4.1 near here>

MX3D has also partnered with Takenaka to produce a structural steel connector (MX3D, 2023b). The connector was designed by engineers from MX3D and Takenaka with the help of a topology optimisation program and is fabricated in duplex stainless steel using the WAAM process. This project demonstrates the suitability of WAAM for the production of highly customised and engineered steel components.

Another example of the application of structural optimisation and WAAM technique has been developed by a research group from TU Delft (Figure 4.2). The Glass Swing has been realised in structural glass and WAAM-produced steel nodes by the Dutch company RAMLAB (RAMLAB, 2018). The non-standard form of the swing was developed through an ad hoc optimisation procedure for vector active glass structures (Snijder *et al.*, 2020).

<Insert Figure 4.2 near here>

Wire and arc additive manufacturing process

Printing setup

WAAM processes can be divided into three main types, depending on the nature of the heat source: (a) gas metal arc welding (GMAW)-based, (b) gas tungsten arc welding (GTAW)-based, and (c) plasma arc welding (PAW)-based. Each type of WAAM technique exhibits specific features. The deposition rate of GMAW-based WAAM is two to three times higher than that of GTAW-based or PAW-based methods. However, GMAW-based WAAM is less stable and generates more weld fume and spatter due to the electric current acting directly on the feedstock. The choice of WAAM technique directly influences the processing conditions and production rate for a target component.

Most WAAM systems use an articulated industrial robot as the motion mechanism. Two different system designs are available. The first design uses an enclosed chamber to provide a good inert gas shielding environment, similar to laser power-bed fusion (PBF) systems. The second design uses existing or specially designed local gas shielding mechanisms, with the robot positioned on a linear rail to increase the overall working envelope. It is capable of fabricating very large metal structures of up to several metres in dimension.

WAAM processes use commercially available wires. These are produced for the welding industry and are available in spooled form and in a wide range of alloys as feedstock materials. The commonly used alloys are: steels and stainless steels, aluminium and titanium. Manufacturing of a structurally sound, defect free, reliable part requires an understanding of the available process options, their underlying physical processes, feedstock materials and process control methods and an appreciation of the causes of the various common defects and their remedies.

Research on WAAM process involves the feedstock, the optimal process parameters and the printing strategy. The feedstock, in form of a wire, can be deposited according to different paths and strategies, with the main process parameters (arc current and voltage, arc transfer mode, speed) being varied accordingly. The deposition process involves complex thermo-physical phenomena, while the solidification conditions promote a microstructure with large columnar grains.

Current WAAM techniques use metal inert gas (MIG) power sources. As an alternative to traditional synergistic machines, cold metal transfer (CMT) can be used, which allows better

heat input optimisation. Modern CMT sources are also characterised by cycle step technology with controlled single spots deposition.

Both traditional synergistic and CMT solutions have been investigated in the literature, although few studies have focused on the influence of WAAM process parameters on microstructural and mechanical properties.

Deposition strategies

Recent applications of WAAM for large-scale structures have exploited two different deposition strategies: (a) a ‘continuous’ strategy (layer-by-layer deposition, suitable for planar and shell elements), and (b) a ‘dot-by-dot’ strategy (for lattice and diagrid structures).

The main applications of the continuous strategy have been: (a) the MX3D bridge, the world’s first metal 3D-printed footbridge installed in Amsterdam, (b) optimised beams realised by Cranfield University and Foster + Partners (LASIMM project), and (c) currently ongoing studies at the Technical University of Darmstadt and the University of Bologna.

Examples of structures realised with the dot-by-dot strategy are: (a) MX3D Cucuyo, a stainless steel café structure, and (b) a diagrid column designed at the University of Bologna and presented at Formnext 2019 expo.

Recent examples of WAAM-produced steel connectors are: (a) MX3D Takenaka connector, (b) the Glass Swing project at TU Delft, and (c) the Albeccular pavilion, designed at the University of Bologna and presented at IASS 2019 (initially conceived with WAAM-produced connectors, then printed in polymers to meet competition rules).

The continuous printing strategy consists of depositing successive layers of welded metal one over the other to create planar or extruded elements with constant thickness. The fundamental process parameters are: (a) the current and its voltage, (b) the wire diameter, (c) the wire-feed rate, (d) the welding speed, and (e) the vertical printed layer height. The combination of such controlling parameters affects both the printing quality (geometrical precision and surface roughness) and the material mechanical properties.

The dot-by-dot printing strategy is an innovative (and still unexplored) WAAM technique to deposit dots of welding metal on a discontinuous process along one axis (Joosten, 2015; Van Bolderen, 2017). The printed outcome results in a one-dimension rod-like element, having constant nominal diameter (as governed by the welding dot) and longitudinal main axis. The specimens considered have been manufactured by MX3D using a commercially available

standard stainless steel welding wire grade ER308LSi (1.2 mm diameter) supplied by Oerlikon.

The welding source commonly used in construction is gas metal arc welding (GMAW) with pulse arc metal transfer. Different cooling strategies can be considered, with the aim of reducing the waiting time between layers and thus reduce the overall printing time.

For structural engineering applications, the need to use a high welding velocity – to achieve rapid realisation of structural elements of such proportions – plays a crucial role for the specific characteristics of the printed parts, as it induces geometric inaccuracy of the outcomes, both in terms of surface roughness and lack of straightness of the elements. For a given element to be printed, a digital model is created with Rhinoceros software (Rhinoceros, 2023). From this model, the printing head reads the coordinates of the points that define, step by step, the position of the welded layer. However, due to intrinsic inaccuracy of the printing process, each point of the digital model has a real counterpart whose position is not exactly the same as that in the digital model as it is affected by an error.

Therefore, when dealing with WAAM-produced structural elements, it is necessary to first codify specific issues related to: (a) the set of process parameters, (b) the wrought material, and (c) the printing strategy. Furthermore, given the novelty of the process, especially for structural engineering applications, there is only a very limited database of experimental results from which to draw information on the structural response of WAAM-produced metallic structural elements.

As previously introduced, structural elements manufactured with current WAAM processes are characterised by peculiar geometrical irregularities and specific material mechanical properties that have to be properly taken into account in both the analysis and design processes.

<A>Design issues for WAAM elements

Geometrical irregularities

WAAM-produced elements are characterised by their inherent geometrical irregularities, which are an inevitable result of the printing process. Such irregularities need to be properly taken into account and fully characterised during the structural design of WAAM-produced elements, as they might affect the structural response of the designed and printed elements.

As far as the continuous printing strategy is concerned, the main issue related to the layer-by-layer deposition is the surface roughness, which also causes variation in thickness of printed specimens (Figure 4.3). For both planar and tubular geometries, additional irregularities in terms of lack of straightness and out-of-roundness should also be studied.

<Insert Figure 4.3 near here>

Therefore, for producing ready-to-use elements and for future applications of on-site metal 3D printing, it becomes crucial to study the geometrical irregularities of WAAM-produced structural elements. First, proper characterisation of the geometry of WAAM-printed specimens should be carried out. From this, the possible influence of these irregularities on the mechanical response of the printed specimens should be considered and analysed.

As mentioned above, for a given planar element to be printed, a digital model from which the printing head reads the coordinates of the points that define, step by step, the position of the welded layer is created with Rhinoceros software. However, due to the geometrical irregularities inherent to the WAAM process, the real printed outcome generally has slightly different geometrical features.

With regards to planar elements realised with a continuous printing strategy, the deposition of successive layers of welded metal results in a non-uniform undulating surface. When considering the uniform rectangular plate represented in Figure 4.4, the origin of the coordinate system used to describe the geometry of the plate is located at one edge. The x and y axes are taken as parallel to the two main directions of the plate, while the z axis is perpendicular to the x - y plane. The thickness of the plate is given by the amount of welded metal positioned by the printing head, which in the digital model has a constant nominal value (t_n) over the plate, equal to 4 mm. In contrast, the thickness of the printed plate is in general not constant, and varies both with x and y , so that $t_{real} = t_{real}(x,y)$. Given that the plate has been produced in a certain printing direction, the effect of the thickness variation on the mechanical behaviour of specimens cut from the plate might be different depending on whether the specimens are cut along the printing direction (x) or perpendicular to it (y).

<Insert Figure 4.4 near here>

Like layer-by-layer deposition, the dot-by-dot strategy is also characterised by inherent geometrical irregularities, which should be properly considered.

The products of dot-by-dot deposition are commonly one-dimension elements (such as rods and bars), as they are developed along a single axis through successive points of welded material. This results in bars of constant nominal diameter, with the diameter being directly related to the drop of welding metal. Usually, the nominal diameter of dot-by-dot-printed bars is 4 to 8 mm. However, for dot-by-dot printed bars, the successive deposition of drops of welding metal results in a non-uniform circular cross-section and non-straight longitudinal axis (formed by the polyline connecting the centroids of all the circular cross-sections). The nominal geometry of the digital model is a uniform full cylinder with straight longitudinal axis (coincident with axis z of the cylindrical coordinate system). The geometry is described by the nominal bar length (L_n) and the nominal cross-sectional diameter (d_n). However, due to the intrinsic imperfections derived by the specific printing process, the outcome is a solid element with non-uniform circular cross-section varying along its length ($d_{real} = d_{real}(z)$) and non-straight longitudinal axis. At a generic height z_i , the centroid of the cross-section is $c_{real} = c_{real}(z)$.

<Insert Figure 4.5 near here>

Material anisotropy

As the manufacturing process may potentially induce an orthotropic behaviour, depending on the orientation relative to the printing direction and the presence of surface roughness resulting from the printing of layers, the mechanical response should be investigated with reference to specimens cut in different orientation with respect to the deposition layers. Figure 4.6 qualitatively depicts three different orientations of specimens cut from continuously printed WAAM plates: longitudinal direction is taken along the deposition layers, transversal direction is taken perpendicular to them, while diagonal direction is taken at 45° from them.

<Insert Figure 4.6 near here>

Possible anisotropic behaviour can also be encountered in dot-by-dot-printed specimens, for which different inclinations of the bars with respect to the vertical longitudinal axis should be considered (Figure 4.7).

<Insert Figure 4.7 near here>

Structural design approaches for WAAM elements

Conventional structural design approach for WAAM

The design approach most widely adopted in international standard building codes, including Eurocodes, is the so-called design value method, also referred to as the semi-probabilistic method (CEN, 2002; Holický, 2009), as first introduced in ISO 2394: General principles on reliability for structures (ISO, 1998).

This method is based on the assumption that no limit state is exceeded when the design values of all basic variables are used in the models of structural resistance R and action effect E . Thus, if the design values E_d and R_d are determined considering the design values of all basic variables, then a structure is considered reliable if the following inequality holds:

$$E_d < R_d \quad (4.1)$$

The action effect depends on the loads and actions applied, while the structural resistance depends on the material properties. Both also depend on the geometrical properties. Generally speaking, all these quantities are taken as random variables whose uncertainties depend also, in addition to the inherent uncertainties of the individual basic variables, on the model uncertainties. Clearly, for design purposes their design values should be considered.

With reference to traditional structures, the material properties (as well as the actions) are taken as random variables, whose distribution is modelled with statistical analysis, while the geometrical properties are typically considered as deterministic values given that their variability is generally negligible when considering traditional manufacturing processes. When dealing with additive manufacturing processes, however, there could also be the need to consider the inherent geometrical variabilities associated with the printing process. The structural model adopted to evaluate the structural response is typically assembled considering beam elements according to the Saint-Venant principle and assuming a linear elastic material behaviour.

The traditional design approach for structures can also be adapted for WAAM elements. The method follows the semi-probabilistic approach to calibrate design values and partial safety factors for the material properties as for traditional structural elements. However, in order to properly consider the design issues for WAAM metals, additional considerations should be made to account for the geometrical irregularities and material anisotropy.

Because of these geometrical irregularities, a detailed description of the mechanical tensile response of the real WAAM element would require the evaluation of local true stress and

strain values, through ad hoc measurements during experimental tests (e.g. with the use of optical monitoring systems). As an alternative, from a structural design point of view, the mechanical response of the entire real WAAM element could be described in terms of the effective mechanical parameters (e.g. effective stresses and strains) that are associated with an effective volume-equivalent cross-sectional area that is uniform along the whole length of the element, as follows:

$$\sigma_{\text{eff}} = \frac{F}{A_{\text{eff}}} \quad (4.2)$$

where A_{eff} is the effective cross-sectional area of the structural member (from volume equivalency) and F is the tensile axial force (e.g. the force applied during a tensile test) (Figure 4.8).

<Insert Figure 4.8 near here>

Clearly, the stress σ_{eff} can be interpreted as an effective stress that differs from the true material stress, conventionally referred to as σ .

The effective stress σ_{eff} depends on A_{eff} , so specific attention should be given to the choice of A_{eff} . Different criteria can be adopted when choosing A_{eff} , based on scientific, technical and practical considerations related to significance, accuracy and reliability of the chosen value. Some possibilities are: (a) use of nominal values, (b) use of a set of punctual values based on mechanical measurements, (c) use of average values as obtained from volumetric measurements. The use of nominal values as given by the manufacturer means there is no need for any measurement, but the absence of measurements may lead to lack of significance and poor reliability, especially for non-standardised processes (such as WAAM).

The use of a few manual measurements (such as caliper measurements) is straightforward since such measurement can be easily executed, even at the production site, but this type of measurement could be easily biased.

The use of average values as obtained from volumetric measurements (used in Kyvelou *et al.*, 2020, and Laghi *et al.*, 2020a) to obtain A_{eff} has the advantage of providing an integral value based on an equal weight criterion. It can also be adopted for fast quality control checks during the production phase.

This result results in all uncertainties (geometrical and mechanical) being condensed into just the mechanical parameters. The simplified approach allows the cross-sectional area to be

treated as a deterministic value, while all the uncertainties are globally collected in the effective axial stress. In this way, the conventional format commonly adopted for the analysis and design of traditionally manufactured steel members, which considers the geometrical parameters as deterministic values and the material strength parameters as random variables, is maintained. Thus, the experimental mechanical parameters become dependent on both the specific geometrical and mechanical features related to the manufacturing process and not only on the material itself.

Design assisted by advanced modelling and non-linear analysis

Within the design workflow of additively manufactured parts and components, advanced numerical models should be adopted to deal with the specific issues related to the printing process, such as the levels of anisotropy, the geometrical imperfections or the residual stresses.

As such, a new design approach – referred to as ‘design by advanced analysis’ – has been developed to take full account of the advantages and characteristics of additive manufacturing technology. The basic principle lies within the concept of the so-called digital twin – that is, the mirroring of a physical object created in a virtual environment by simulation-based engineering (Okita *et al.*, 2019).

Theoretically speaking, the use of advanced simulation tools and digital twins would allow the modelling of the geometrical imperfections of every single manufactured piece and to consider the actual orthotropic non-linear stress–strain material behaviour such that all the potential modes of failure could be explicitly included in the model. Such complex and detailed finite element models would even allow simulation of loading tests, construction sequences, fatigue-related issues and other complex non-linear phenomena. These advanced analysis models may also be used along with structural monitoring systems for real-time control of the structural response. Pioneering research in this direction is currently under development by various research groups, including the research team led by Alan Turing Institute and MX3D in collaboration with Imperial College London and Autodesk that developed a digital twin model of the MX3D bridge recently installed in Amsterdam city centre.

The full development of a reliable digital twin requires detailed knowledge of the peculiar geometrical imperfections, requiring the use of random field approaches and uncertainty quantification techniques (Bae *et al.*, 2004), as well as ad hoc material models able to account

for the specific features of WAAM. In order to properly manage such advanced simulation tools, structural engineers need to become more computationally literate and acquire high-level computational skills (Buchanan and Gardner, 2019).

Computational design approach

Recently, a paradigm shift has occurred in the structural design workflow thanks to the computational design concept, which fully embraces the use of computation for the exploration of structural solutions and the development of novel design ideas.

Within the computational design framework, several different approaches have been proposed so far. Cascone *et al.* (2021) recently proposed a structural grammar approach for the generative design of diagrid-like structures. A similar concept has also been adopted to realise a WAAM diagrid column (Laghi *et al.*, 2020b). Generative design has also been used by Wang *et al.* (2021) in an integrated method to create joints for tree-like columns to be realised using additive manufacturing. Alternatively, topology optimisation algorithms have been implemented to consider the features particular to the additive manufacturing process (Saadlaoui *et al.*, 2017; Wang *et al.*, 2020).

With reference to the latter, Kanyilmaz and Berto (2019) recently proposed innovative steel tubular joints designed by making use of topology optimisation and metal additive manufacturing techniques to mimick features present in nature.

With the aim of integrating the capabilities of optimisation procedures in terms of new structural shapes with the current limitations of WAAM technology (i.e. manufacturing constraints, printing precision and material properties) together with the robustness and reliability of structural design verifications, a so-called ‘blended’ structural optimisation approach was recently proposed. The approach is intended to blend a stiffness-based topology optimisation approach (suitably tailored for WAAM stainless steel, see for example Bruggi *et al.*, 2021) with the basic principles of structural design, in terms of conceptual design and structural solutions to conceive an initial design, together with concepts of robustness and reliability, to guide the designer from the purely mathematically optimised solutions towards the final design (Figures 4.9 and 4.10). The fundamental aspects of the blended design approach are (a) the basic principles of structural design, (b) the

manufacturing constraints proper of WAAM, (c) the topology optimisation algorithms, and (d) the numerical simulations to verify the structural performances.

<Insert Figure 4.9 near here>

<Insert Figure 4.10 near here>

This approach has been used to design an optimised stainless steel I-type beam for a residential building (Figure 4.11), accounting for the anisotropic nature of WAAM stainless steel printed using the continuous strategy. A similar approach was also adopted to design a WAAM diagrid column for fabrication using the dot-by-dot strategy, which became the first example of a WAAM lattice structural element. The design of the column minimises material use but prevents local and global buckling. The column was also awarded the ‘Special Mention by Autodesk’ at 3D Pioneers Challenge 2021 in the Construction category (Laghi *et al.*, 2020b).

<Insert Figure 4.11 near here>

<Insert Figure 4.12 near here>

Mechanical performances of WAAM elements for construction

Extensive experimental characterisation has been carried out by several research groups on various alloys. For construction-related applications, stainless steel and mild steel alloys have been studied to assess the key mechanical parameters in terms of (a) the inherent material anisotropy and (b) the geometrical irregularities of the printed parts.

Research work carried out at the University of Bologna investigated the geometrical and mechanical features of WAAM-produced 308LSi stainless steel plates, with the aim of ascertaining the key mechanical parameters for structural design purposes. Tensile tests were performed on dog-bone shaped specimens cut at various angles from the deposition layer (i.e. 0°, 90° and 45°) (Figure 4.13). Some of the specimens were milled to erase the surface roughness, while the others were left as fabricated. The results from the geometrical characterisation revealed that, in general, the manufacturing process is characterised by limited precision, resulting in non-negligible surface roughness (of the order of 0.20–0.30 mm) and consequential thickness variability of the plate of the order of 5%. The results from the mechanical characterisation revealed that the key mechanical parameters are severely affected by the material anisotropy inherent in the printing process, which creates

preferential crystallographic orientation with respect to the printing direction. This affects the macro-mechanical properties in terms of both stiffness and strength. The most interesting results were for Young's modulus. For specimens cut along the longitudinal and transversal directions (i.e. 0° and 90°), Young's modulus was on average 110–140 GPa, while for those cut along a diagonal direction (45°) it was around 240 GPa. These outcomes were then used to calibrate a specific anisotropic elastic model for WAAM-processed austenitic stainless steel, considering an orthotropic constitutive law.

<Insert Figure 4.13 near here>

The same results were obtained by a research group from Imperial College London, who additionally calibrated an orthotropic material model for the post-elastic behaviour of WAAM-produced stainless steel plates. Additional experimental work has included flexural and buckling behaviour of circular and square hollow cross-sections, as well as the definition of the 'design assisted by testing' procedure for the world's first footbridge entirely realised using WAAM.

Regarding dot-by-dot products, first investigations were carried out at the University of Bologna to assess the influence of the build angle on the geometrical and mechanical features of WAAM stainless steel bars (Figure 4.14). The results highlighted the detrimental effect of increasing build angle, with a limit set to 45° from the vertical axis. Similar results were also obtained by a research group at ETH Zurich for WAAM mild steel bars printed at different nozzle and build angles.

<Insert Figure 4.14 near here>

Design values and partial safety factors for structural applications

The mechanical parameters determined by the experimental investigations allow the calibration of the first design values and partial safety factors of WAAM base material for structural design applications.

With reference to the procedure reported in Eurocode 0 (CEN, 2002), design values related to the resistance as the material property (X_d) can be defined from the results of experimental tests. In particular, Annex D defines a procedure to derive design and characteristic values of a material property for a new material (as in the case of WAAM base material) through the so-called 'design assisted by testing' procedure.

Following this procedure, the research group from the University of Bologna in collaboration with TU Delft calibrated design values of the key mechanical parameters (i.e. yielding and ultimate tensile strength) for WAAM stainless steel from statistical interpretation of the experimental results (Figure 4.15). Different design values were calibrated for each of the three main printing orientation (i.e. 0°, 90° and 45°), accounting for the anisotropic nature of WAAM stainless steel. From these, the corresponding partial safety factors were extracted. In general, the results showed good agreement with the values suggested in Eurocode 3 for stainless steel structures. These preliminary results are the first reference for structural engineers and producers dealing with the design of structures realised with WAAM members. The long-term objective would be to provide specific contributions to deliver guidelines for the structural design of members realised with WAAM technology.

<Insert Figure 4.15 near here>

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Figure 4.1 MX3D footbridge realised with WAM process and presented at the Dutch Design Week 2018 in Eindhoven

Figure 4.2 The Glass Swing realised at TU Delft in collaboration with the Dutch

company RAMLAB (Snijder *et al.*, 2020)

Figure 4.3 Close-up views of the surface irregularities inherent to WAAM-produced specimens: (left) surface roughness from continuous printing strategy (planar element) and (right) diameter variability from dot-by-dot printing strategy (bar)

Figure 4.4 Digital model and corresponding printed element of a WAAM-produced plate from which 'dog bone' specimens are extracted

Figure 4.5 Digital model and corresponding printed element of a WAAM-produced bar

Figure 4.6 Orientations of 'dog bone' specimens cut from a plate with respect to the deposition layer

Figure 4.7 Graphical representation of rod elements printed in three different orientations: vertical at 0° (aligned with the vertical direction of deposition), inclined at 10° and 45° (from the vertical direction of deposition)

Figure 4.8 Nominal, real and effective thickness for planar WAAM specimen

Figure 4.9 Fundamental aspects of the blended structural optimisation approach

Figure 4.10 Conceptual flowchart of the blended structural optimisation approach

Figure 4.11 Conceptual design of optimized I-type beams for a multi-storey steel frame building

Figure 4.12 Conceptual design of WAAM diagrid column

Figure 4.13 Mechanical features of WAAM stainless steel plates

Figure 4.14 Mechanical features of WAAM stainless steel bars

Figure 4.15 Statistical analysis of ultimate tensile strength in the three main directions relative to the printing direction: (a) longitudinal, (b) transverse and (c) diagonal