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RESEARCH PAPER

Mechanical properties of wire plus arc additive manufactured steel and stainless steel structures

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Abstract
As the imagination, need, and desire for large additively manufactured metallic structures grow across market sectors, so interest in wire plus arc additive manufacture (AM) techniques is growing. Often, the first requirement of a potential new user of AM is knowledge of the mechanical properties of common materials, process accuracy, reliability and productivity, and the implications of these manufacturing parameters on the structural integrity of their application of interest. This paper will examine the use of a robotic gas metal arc welding system to build test structures in the 0.5 m, 20 kg range from low carbon steel and stainless steel, using the wire plus arc additive manufacturing technique. Different approaches to build methodology and their effects on the mechanical properties including yield and tensile strength, impact, fracture toughness, and anisotropy will be examined and interactions and co-relations identified. The technology is shown to be capable of producing steel structures with very high fracture toughness, with some loss of strength, when compared with equivalent parent metal and welds. The specific arc deposition pattern affects both the mechanical properties and the apparent anisotropy in both the carbon steel and stainless steel. The experimental results generated are considered and comments made in relation to their implications for structures manufactured in this manner.

Keywords Wire · Arc · Steels · Stainless · Build method · Strength · Impact · Toughness · Additive manufacturing

1 Introduction

As the imagination, need, and desire for large additively manufactured metallic structures grow across market sectors [1], so interest in wire plus arc additive manufacture (AM) techniques is growing. Often, the first requirement of a potential new user of AM is knowledge of the mechanical properties of common materials, process accuracy, reliability and productivity, and the implications of these manufacturing parameters on the structural integrity of their application of interest. Although there is some information in the public domain about the fracture toughness of additive manufactured alloys such as Ti-6Al-4V or Inconel 625, often made using electron-beam or laser powder bed manufacturing [2–6], very little data has been published about the performance of steels when used in arc additive manufacturing. However, existing literature does indicate that the orientation of the fracture path in relation to the build direction will affect the performance of the alloy in relation to conventional wrought material [7, 8].

To provide industry with some baseline data on the performance of common engineering steel and stainless steel, TWI carried out some deposition trials using arc additive manufacturing (arc-AM) to create free-built walls of deposited metal 30 mm thick from which to extract a set of mechanical test specimens for tensile, Charpy, and fracture toughness testing. The data generated is intended to help potential users of this technology gain confidence in developing it for application to larger scale structures.

This article is part of the collection Welding, Additive Manufacturing and Associated NDT

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2 Generating arc-AM carbon and stainless steel samples

2.1 Materials and consumables selection

Two alloys were investigated in this work. The first was a low alloy steel consumable, typical of those used for girth welding of pipelines with grades to API 5L X65 [9]. The consumable was Lincoln Supramig Ultra ER-70S. The second alloy was an austenitic stainless steel consumable, Lincoln LNM ER316L-Si, typically used to weld equivalent austenitic stainless steel components. Austenitic stainless steel has been used for additive manufacturing described in published literature [10], but no fracture toughness data has been presented to show how it performs in relation to more standard stainless steel product forms.

2.2 Deposition process assessment and stability

The arc-AM deposition used a robot-mounted gas metal arc welding torch, and the process parameters were developed to find the optimum transfer mode between cold metal transfer (including pulsed and alternating current where appropriate), dip transfer (including pulsed current), and spray transfer (including pulsed current). Deposition parameters were developed to deposit different bead widths. During the deposition of the metal, a number of parameters were monitored. These included the arc voltage, current, wire feed speed, and torch linear velocity; visual assessment of melt pool size in-process and measurement of bead width, height, profile, placement accuracy, and interpass temperature between layers. These were adjusted where necessary in order to develop a method to deposit a free-standing wall of material of consistent geometry, layer height, and interpass temperature.

It was initially found that the size of the melt pool increased as heat built up over successive deposition layers to the point where molten metal began to run down the edge of the wall. By selecting arc parameters which had a reducing heat input during the first three layers, it was possible to achieve a consistent bead shape. The heat input for layer four and upwards was approximately half that of the first layer deposited. For reference, heat input was initially calculated in the manner used for conventional welding:

$$\text{Heat input} = \eta \frac{60VI}{1000v}$$

where η is process efficiency, V is arc voltage, I is arc current, and V is linear velocity.

Control of heat input was most often achieved by modification of arc voltage to reduce energy input without changing the rate of metal addition or linear process speed, with a deposition rate of approximately 3.5 kg/h. No heat treatment or post processing was applied to the material after deposition and before mechanical testing.

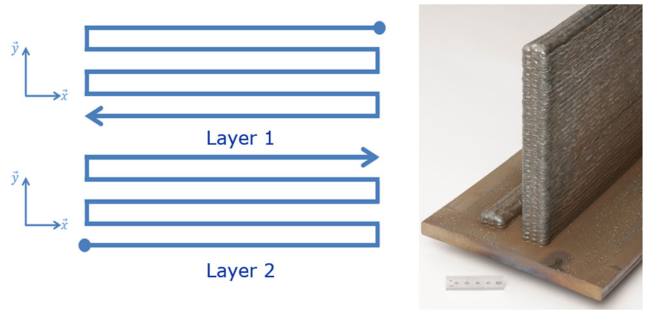

Fig. 1 Parallel bead deposition technique

2.3 Bead deposition techniques

Two different approaches were used for depositing the arc-AM walls, depending on how the welding torch was moved when depositing each layer. The first method was a parallel bead technique whereby a single bead was woven lengthwise within the layer. The direction and start point was reversed for each layer (Fig. 1). The second method was an oscillating deposition technique whereby a single bead was woven widthwise within the layer. The direction and start point was again reversed for each layer (Fig. 2).

Arc-AM deposits measuring 500 mm long by 30 mm wide and 250 mm tall were manufactured using common deposition parameter sets, both bead deposition patterns, and in both carbon steel and stainless steel, from which mechanical test specimens could be extracted. A test programme was designed to compare both bead deposition techniques for both alloys, and the orientation effect of properties in the direction parallel to the deposition layers and perpendicular to the layers.

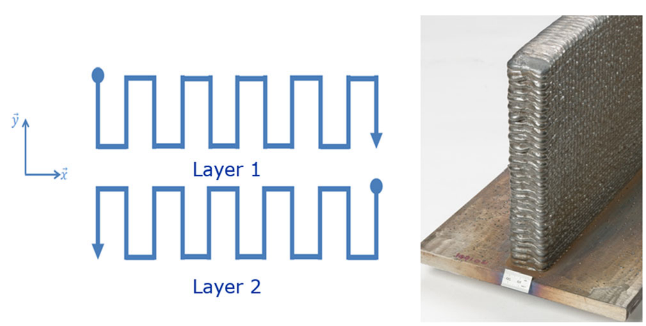

Fig. 2 Oscillating bead deposition technique

3 Mechanical testing

3.1 Test programme

From each arc-AM wall sample, the following test specimens were extracted:

- Six round tensile specimens with a gauge diameter of 10 mm (three specimens extracted aligned parallel to the build layers, and three specimens aligned perpendicular to the build layers). The tensile tests were carried out at room temperature to BS EN ISO 6892-1:2009 to generate full stress-strain curves.
- Six single-edge notched bend (SENB) fracture toughness test specimens with dimensions 15 mm × 30 mm × 150 mm (three notched parallel to the build layers, and three notched perpendicular to the build layers). The specimens were tested in accordance with BS 7448 Part 1 at − 20 °C for the carbon steel (typical of the lowest service temperature that X65 line pipe is used for), and the stainless steel was tested at room temperature (since austenitic materials do not show a ductile to brittle transition with reducing temperature).
- Six Charpy specimens 10 mm × 10 mm × 55 mm machined with a vee notch. Three specimens were notched parallel to the build layers, and three specimens perpendicular to the build layers, and all were tested at room temperature to BS EN ISO 148-1:2010. For the carbon steel material, ten further Charpy specimens were tested for each deposition technique and orientation, at a range of temperatures to generate ductile to brittle transition curves.

Further small specimens were extracted for basic metallographic analysis and to allow the chemical composition of the deposited metal to be analysed using optical emission spectroscopy, enabling comparison with the equivalent material grades.

3.2 Notch orientation

The Charpy and fracture toughness specimens were extracted in two different orientations so that specimens were tested with the notch or crack parallel to the deposition layers (identified as *Z–X* orientation), and also with the notch or crack aligned perpendicular to the layers (identified as *X–Z*). These orientations are illustrated in Fig. 3, shown against an *X–Y–Z* coordinate system for the built material. The tensile specimens were described as being aligned along either the *X*- or *Z*-axes. Figure 3 shows the alignment of specimens, not actual locations; a cutting plan was developed which distributed the required samples at different locations through the wall with minimal material wastage.

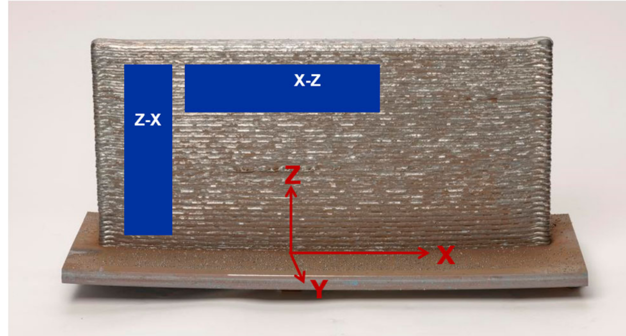

Fig. 3 Notch orientations parallel to the deposition layers (*Z–X*) and perpendicular to the layers (*X–Z*)

3.3 Comparison data

Testing on equivalent conventional X65 and 316L steels was not carried out as part of this research. However, comparison data for tensile, Charpy, and fracture toughness properties for these materials was sought from literature [11–19], and from historical testing carried out at TWI (but not in the public domain). Comparisons were made between the properties achieved in the arc-AM material, and equivalent conventional parent material, and also its welds where data was available.

4 Results

4.1 Carbon steel strength

The ER70-S weld consumable is expected to give minimum yield strength of 400 MPa for welding use, based on information from the consumable supplier [19]. This type of consumable is often used to weld X65 pipeline, which has a specified minimum yield strength (SMYS) of 448 MPa [9].

However, the tensile properties from the arc-AM metal deposited using this consumable gave lower tensile values than these. For the parallel bead deposition, the stress-strain curves are shown in Fig. 4, and it gave a yield strength along the *X*-axis (parallel to layers) of 381–402 MPa, while the strength along the *Z*-axis (perpendicular to the layers) was much lower at 308–5317 MPa.

When an oscillating bead deposition technique was used, the strength was still lower than X65 pipe specification, but gave a slightly higher yield strength along the *X*-axis of 346–360 MPa, while showing less effect of orientation with similar strength values along the *Z*-axis of 328–351 MPa, although the percentage elongation was a little less. The stress-strain curves for the oscillating bead deposition are shown in Fig. 5.

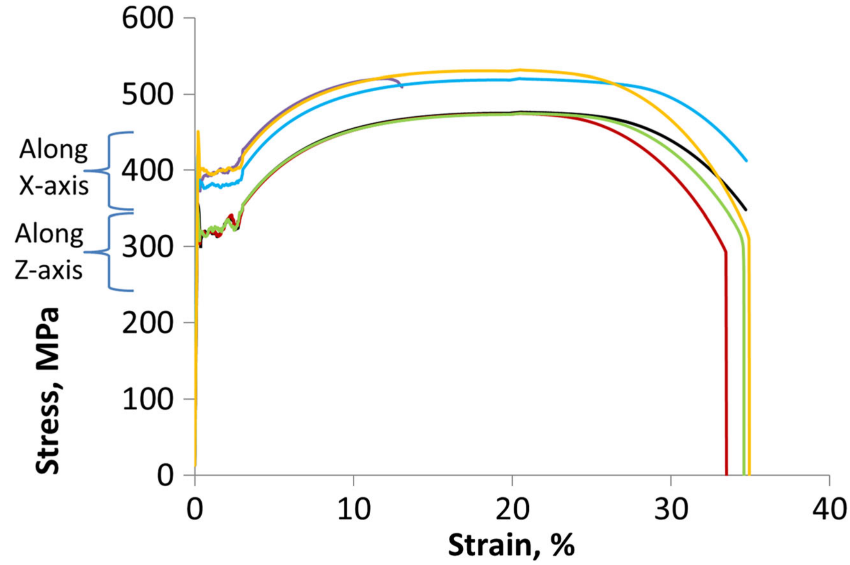

Fig. 4 Stress-strain curves for carbon steel specimens aligned along the *X*-axis (parallel to build layers) and *Z*-axis (perpendicular to the layers) for parallel bead arc-AM material

4.2 Carbon steel toughness

The Charpy ductile to brittle transition data for specimens from the arc-AM carbon steel deposit gave properties that were fairly consistent between the two specimen orientations and only weakly affected by the bead deposition technique, as shown in Fig. 6. The specimens notched parallel to the layers gave slightly higher room temperature upper shelf toughness than the specimens notched perpendicular to the layers. Parallel specimens gave 234 J average in the parallel bead deposition and 255 J average in the oscillating bead, whereas across the layers, the upper shelf Charpy results for both bead deposition methods was 215 J. A tanh curve function fitted to all the ductile to brittle data gave a T_{27J} temperature of − 88.5 °C, indicating excellent notch toughness.

Comparison data was found from previous Charpy testing performed on Grade X65 pipe material, welds, and HAZ, as well as some data from literature sources [11, 12]. This is plotted together in Fig. 7 and shows that the arc-AM Charpy properties are lower than some of the data on conventional rolled parent metal (PM) to API 5L X65, but exceed the value of weld metal (WM) in these materials, and are somewhat similar to the few heat-affected zone (HAZ) values that were found for comparison.

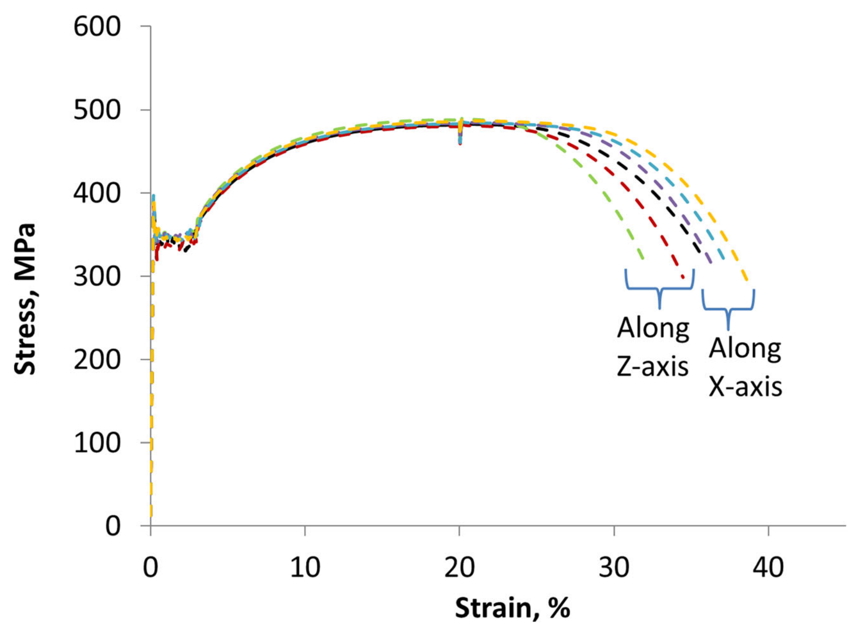

Fig. 5 Stress-strain curves for carbon steel specimens aligned along the *X*-axis (parallel to build layers) and *Z*-axis (perpendicular to the layers) for oscillating bead arc-AM material

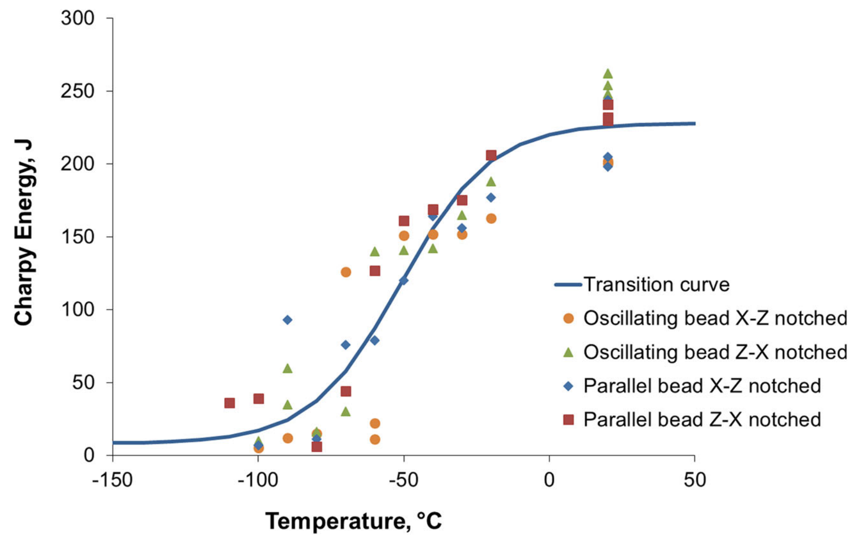

Fig. 6 Charpy impact data and ductile to brittle transition curve fit for carbon steel arc-AM specimens

The story is different when instead of Charpy impact toughness, fracture toughness test results are compared, as shown in Fig. 8. The results, all from tests carried out at −20 °C, are given in terms of crack tip opening displacement (CTOD), to allow comparison with other data sources that provided toughness data only in terms of CTOD [13]. There is some effect of the deposition technique, with the parallel bead showing the highest fracture toughness results when notched parallel to the deposited layers (2.2 mm average CTOD), and a recognizable reduction in toughness when notched perpendicular to the layers (1.75 mm average CTOD). The oscillating bead technique showed very consistent fracture toughness for the notch orientation. Both deposition techniques gave very high fracture toughness values (1.98 mm average CTOD for all six results). These fracture toughness values were far in excess of the typical values being measured on X65 steel and its welds, which were typically less than 1 mm of CTOD. One of the arc-AM specimens ended in a fracture event when tested (despite giving a CTOD value of 0.9 mm). When the fracture faces from this specimen were examined, a pore was present just at the fatigue pre-crack tip location (shown in Fig. 9), which was considered to be in some part, the reason for the markedly different result from this specimen in comparison with the other arc-AM specimens. The fracture faces of the SENB tests in arc-AM carbon steel showed no texture effect of the deposition process in the appearance of the final fracture.

Post-test metallography was performed to investigate the location of the fracture initiation in this specimen (Fig. 10). The microstructure of the carbon steel arc-AM deposit is generally comprised of an extremely fine grain size, accounting for the otherwise high fracture toughness values. However, at

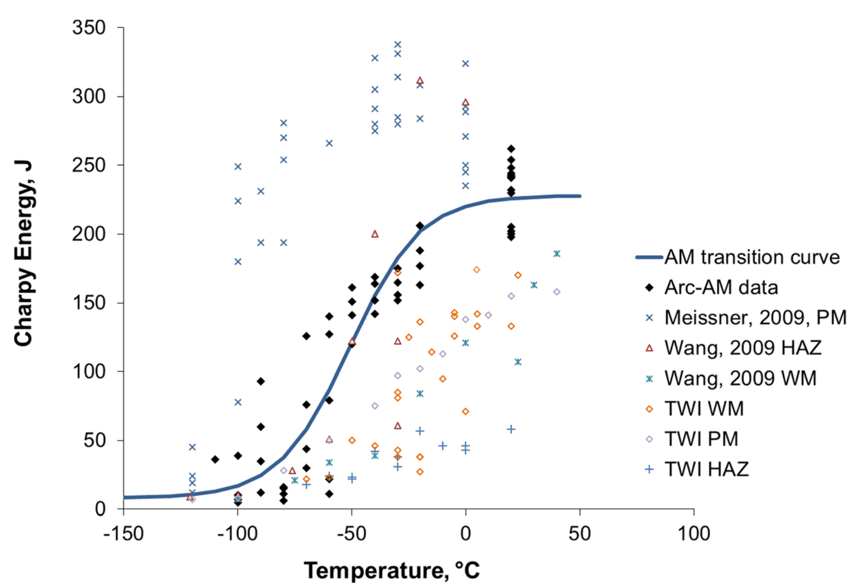

Fig. 7 Charpy data from all the arc-AM specimens (in black) compared with equivalent data for conventional X65 steel parent and weld metal, and HAZ

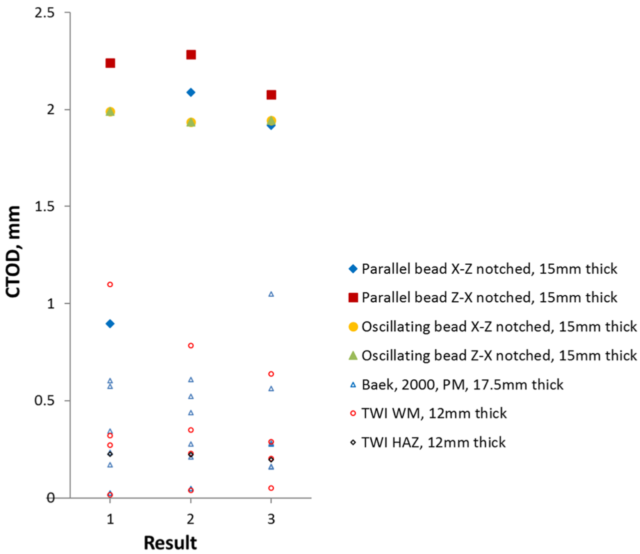

Fig. 8 Fracture toughness data (in terms of CTOD) for arc-AM carbon steel and reference data, all at − 20 °C

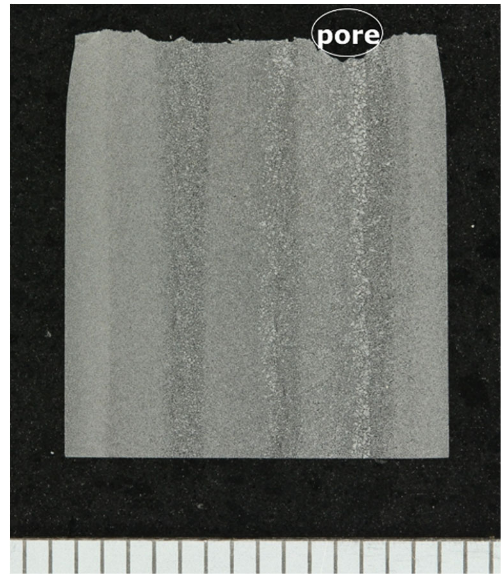

Fig. 10 Section perpendicularly through the pore location of the fracture face on the right hand side in Fig. 9, showing a band of coarser grains at the pore location

the location of the pore, the microstructure was also at its coarsest, showing a band of coarser grains at the location of the pore, which further explains this one outlier result.

4.3 Stainless steel strength

The stainless steel grade 316L has a specified minimum yield strength of 25 ksi (170 MPa), but is expected to give typical yield strengths of around 300 MPa. The Lincoln ER316L-Si weld consumable is expected to give typical all-weld metal yield strength of 452 MPa, based on the data sheet from Lincoln [19].

All the mechanical testing on the stainless steel was carried out at room temperature to allow comparisons to be made easily between different mechanical properties, the two bead deposition techniques, and the experimental and consumable data. As no particular service temperature was of concern, the absence of a ductile to brittle transition for stainless steels reduced the need to specifically capture lower temperature performance.

Fig. 9 Fracture faces from the carbon steel SENB specimen giving a fracture result after acheiving CTOD of 0.9 mm

The results of the tensile tests on the arc-AM material showed that in the parallel bead deposit, the yield strength parallel to the build layers was 304–312 MPa, while perpendicular to the layers, it was a little lower at 283–289 MPa. The oscillated bead showed consistently higher strength, with yield strength parallel to the layers of 372–422 MPa, but again, a little lower perpendicular to the layers which had yield strength of 324–331 MPa. The stress-strain curves for the arc-AM stainless steel material are shown in Fig. 11.

Although all the arc-AM results exceeded the specified minimum for 316L stainless steel, they were still significantly under-matching the strength expected from the consumable certificate for typical conventional arc welds.

4.4 Stainless steel toughness

The results from the Charpy testing on the stainless steel arc-AM material are shown in Fig. 12, alongside data from literature [14].

The Charpy tests performed here were carried out at room temperature, and it was difficult to find data for comparison, since much published Charpy data on this material was done at − 196 °C for instance for validation for application to storage of liquefied natural gas. Austenitic stainless steel does not show a ductile to brittle transition with temperature, but the differences in the tensile properties at these two test temperatures will affect the relative impact energies, making comparison between room temperature and cryogenic performance not completely equivalent.

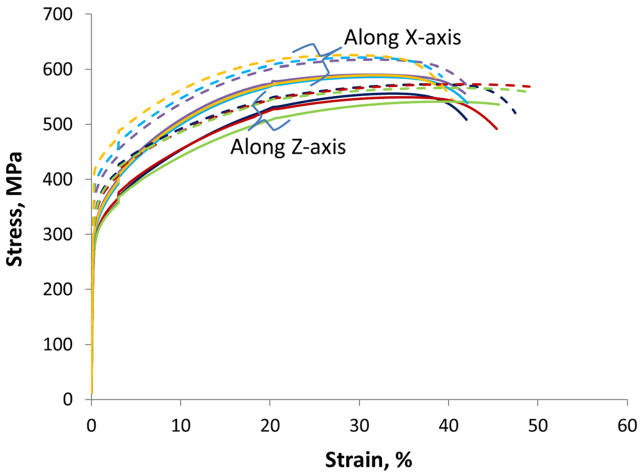

Fig. 11 Stress-strain curves for 316L arc-AM specimens aligned along the *X*-axis (parallel to build layers) and *Z*-axis (perpendicular to the layers). Data for parallel bead deposition are shown solid lines, and oscillating bead deposition are shown dashed

For the arc-AM material from the parallel bead deposit, the specimens with *Z–X* notches (notch parallel to layers) gave an average Charpy impact energy of 143 J. The specimens with *X–Z* notches (notch perpendicular to the layers) gave an average of 126 J, again showing that the best properties are along the layers rather than across them. This trend was also seen in the specimens from the oscillating bead deposit, but all the Charpy test results were around 5–10 J higher with the oscillating bead compared with the parallel bead. The Charpy impact toughness was higher than data reported from literature for parent material [14].

However, when the fracture toughness results were compared with literature data, of which more could be found, the results were within the scatter band of parent metal 316L stainless steel data. The fracture toughness results for the 316L stainless steel arc-AM materials are shown in Fig. 13, plotted alongside literature, and TWI data. The fracture toughness is shown in terms of stress intensity factor, *K* (rather than CTOD this time), to compare directly against the fracture parameters reported in literature. The experimental values of fracture toughness determined in terms of J_{mat} were converted to values of K_{mat} using the following equation, from [20], and assuming a modulus of elasticity of 201,000 MPa and Poisson's ratio of 0.3.

The fracture toughness of the arc-AM material had highest toughness from the parallel bead deposition when notched parallel to the layers (average *K* of 554.3 MPa√m, average CTOD of 1.91 mm). The same material notched across the layers gave an average *K* of 476.4 MPa√m (average CTOD of 1.35 mm). The oscillating bead deposition material was again less consistent with notch orientation, and showed average *K* of 474.7 MPa√m (1.30 mm CTOD) parallel to the layers, and average *K* of 466.6 MPa√m (1.26 mm CTOD) across the layers.

It is interesting to note that Charpy properties were highest in the oscillating bead deposit, while fracture toughness properties were highest in the parallel bead deposit; an observation that these two "toughness" tests are measuring slightly different, albeit related, properties. The fracture appearance of the SENB specimens in the stainless steel is shown in Fig. 14, and some texture of the layers can be seen in the fatigue pre-crack and final fracture of the specimens.

It was possible to find comparison fracture toughness data from two published papers [16, 17], as well as from TWI data, which has been published in [18]. A further comparison was made with values from API 579/ASME FFS-1 Annex 9F [15],

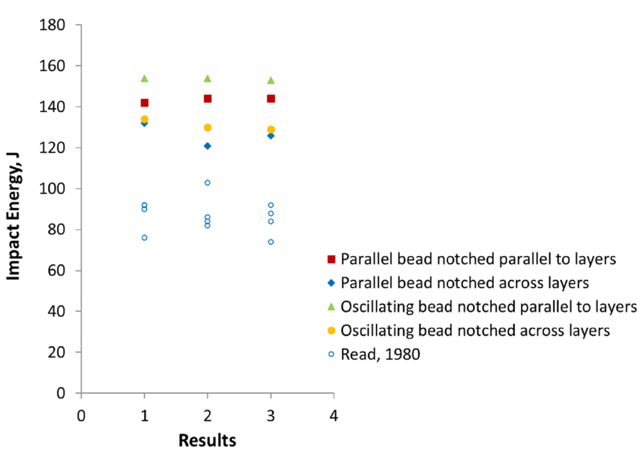

Fig. 12 Charpy data from 316L stainless steel arc-AM specimens compared with equivalent data from literature

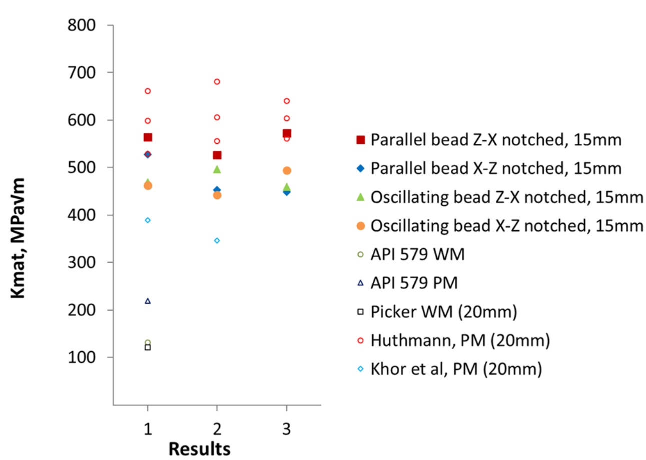

Fig. 13 Fracture toughness data (in terms of K_{mat}) for arc-AM stainless steel and reference data, measured at room temperature

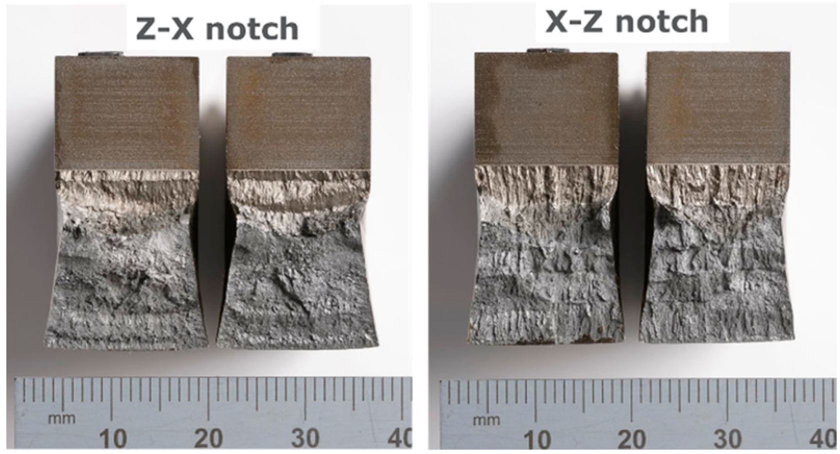

Fig. 14 Examples of fracture faces from SENB specimens in arc-AM 316L stainless steel for two different notch orientations

which provides lower bound values of fracture toughness for austenitic stainless steels, in order to ensure conservative assessments of crack-like flaws. Therefore, the values from API 579/ASME FFS-1 should be much lower than measured parent metal values, which they are, and similar to the one other weld properties reported. The arc-AM values of fracture toughness were on the lower end of the parent metal comparison values, but comfortably in excess of the fracture toughness that might be expected in weld metals.

5 Discussion

5.1 Summary

Wire plus arc additive manufacturing was used to develop procedures to manufacture free-standing walls of material 30 mm thick in both carbon steel, and austenitic stainless steel. Two different bead deposition techniques were compared; using parallel bead deposition in each layer and using an oscillating bead deposition in each layer. The strength, impact, and fracture toughness of each material was characterized, and although the strength of each was lower than might have been expected from the weld consumables when used in a conventional weld, the Charpy and fracture toughness was generally high, when compared with carbon steel and austenitic stainless steel properties when tested in their conventional product forms. A summary of the different properties and which deposit and which specimen/notch orientation gave the superior properties is given in Table 1.

5.2 Effect of bead deposition technique

A microstructural analysis was not part of this work; however, some metallographic sections were prepared for example Fig. 10. It was apparent from these sections that both deposition techniques resulted in unusual and sometimes heavily textured microstructures. It seems clear that the deposition technique and the resulting thermal profile, along with the direction of cooling heat flux, have a profound effect on grain size and orientation within and between layers and that these features have an effect on the mechanical properties achieved.

As shown in Table 1, both bead deposition techniques showed promising mechanical properties. The stainless steel gave the highest strength when deposited using the oscillating bead, whereas carbon steel was stronger with the parallel bead

Table 1 Summary of the highest mechanical properties for arc-AM steels for different bead deposition and orientation relative to the layers

Property (highest value)	Material	Parallel bead deposition	Oscillating bead deposition
Yield strength	Carbon Steel	Parallel to layers	
	Austenitic stainless steel		Parallel to layers
Charpy impact toughness	Carbon Steel		Parallel to layers
	Austenitic stainless steel		Parallel to layers
Fracture toughness	Carbon Steel	Parallel to layers	
	Austenitic stainless steel	Parallel to layers	

deposition. This suggests that the bead deposition technique for arc-AM cannot be generalized, but that with consideration for the properties required at any point within a structure, the deposition technique such as parallel, oscillated, or other types of bead placement strategy or combinations of all these and the resulting microstructure could be optimized for the particular alloy and component being fabricated. However, this is a task of significant complexity and the use of high-integrity process modelling may be required to achieve it. The work presented here also demonstrates the difference in mechanical properties that can be achieved by adapting the bead deposition technique; a difference in strength of 40 MPa in favour of parallel beads in the carbon steel and up to 100 MPa improvement when oscillating beads were used for austenitic stainless steel.

When it came to toughness properties, both materials were consistent, with both showing better Charpy results in the oscillating bead material and better fracture toughness in the parallel bead material. The difference in the toughness properties between the two deposition techniques was not as great as for the tensile properties. This may be a consequence of the fracture behaviour being governed by a very small plastic zone at the tip of the crack, whereas the tensile properties capture the bulk yield behaviour of the entire layer, characterizing the differences between the bead placement patterns. This again suggests that the arc-AM bead deposition technique could be optimized to improve the strength without imposing a significant penalty in terms of fracture toughness.

5.3 Effect of orientation relative to build layers

All of the mechanical properties showed their best performance in the orientation aligned in the plane of the deposited layers and showed lowest strength and toughness when the specimen or notch/crack was aligned perpendicular to the layers. The oscillating bead deposition in the carbon steel showed the most consistent similarity in properties between the X and Z orientations for strength and Charpy impact toughness properties, but the fracture toughness was significantly lower across the layers. In the stainless steel, both deposition techniques consistently showed significantly worse properties across the layers.

The effect of deposition orientation on the mechanical properties will be important when designing arc additively manufactured components to ensure that the highest strength is in the direction of the highest principal stresses when loaded. Likewise, that most likely flaws expected in the component (such as lack of fusion flaws) are oriented along the plane of the layers, and that flaws oriented transversely (like solidification cracking or stop-starts) might be more of a concern for the component integrity and need to be controlled.

5.4 Feasibility of arc-AM for high-integrity structures

The gas metal arc trials presented here for depositing AM material for high-integrity structures have shown that the technology shows great promise for a wider range of potential applications than might have been considered at the early development of AM technologies. The main concern that has been highlighted here is that the strength of arc-AM material is always, but not consistently or predictably, lower than that expected for the consumable under conventional welding conditions, meaning that the weld consumable certificates cannot be relied upon to predict the strength of the arc-AM deposit. It should be borne in mind that the consumables used were designed to form the most favourable grain structures and mechanical properties under a well-defined and easily predictable process and thermal profile. However, the thermal profile of AM is significantly different. If a single point in the middle of a layer is considered, in parallel bead deposition, it will experience multiple heating and cooling cycles in every layer as adjacent beads are deposited, whereas the same point experiences only a single heating and cooling cycle in an oscillated deposition, but the time at temperature and cooling rate is much slower. For several reasons including maximizing productivity, a very high interpass temperature is used in AM (400 °C in this work), this results in a much longer time at elevated temperature and low cooling rate for any AM deposition technique when compared with conventional welding,

However, any strength loss is mitigated by a potential improvement in the fracture toughness of the arc-AM material. For carbon steels, the AM deposits exhibited fracture toughness superior even to the parent metal it was compared with. The high fracture toughness is associated with the fine grain size achievable with the AM process; giving grain sizes smaller than those in typical rolled parent steel. The effect of grain size and orientation can affect the behaviour at the tip of a crack (i.e., its fracture toughness) in different ways to the bulk tensile properties (such as yield strength). In stainless steel, the toughness was only slightly below other parent metal data and well above any recorded weld metal data.

Both alloys showed improved fracture toughness in relation to conventional welds using these types of consumables. However, flaws such as porosity and variations in grain size can affect toughness, increasing scatter.

The impressive values of fracture toughness that have been achieved in these arc-AM carbon and stainless steels suggest that additive manufacturing could show good promise for high-integrity fabrication but that the use of “welding” consumables for AM may be inappropriate. It is suggested that in the future, consumables designed to work under AM conditions will be required in order to achieve the best possible mechanical properties.

6 Conclusions & Recommendations

The conclusions from this research are that:

- Wire plus arc AM has the potential to achieve high fracture toughness in deposits of carbon steel and stainless steel, for potential use in high-integrity applications.
- The details of the bead deposition pattern can have a strong effect on the strength of the AM material.
- Arc-AM deposits tend to under-match the strength expected from the same consumable under conventional welding conditions, which should be considered when selecting consumables for arc-AM.
- Development of a better understanding of the deposition technique/microstructural evolution/properties relationships of AM is required.
- Design of deposition procedures and consumables specifically for AM may be required to achieve the best possible combination of mechanical properties.

The recommendations for further work would be:

- The investigation of other potential bead deposition techniques and their effect on microstructural evolution and mechanical properties, in these and different alloys.
- To develop consumables specifically for use under AM conditions.

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References

1. Frazier W (2014) Metal additive manufacturing: a review. J Mater Eng Perform 23(6):1917–1928
2. Puppala G., Moitra A., Sathyanarayanan S., Kaul R, Sasikala G., Prasad R. C. and Kukreja L. (2013) "Evaluation of fracture toughness and impact toughness of laser rapid manufactured Inconel-625 structures and their co-relation", 13th international conference of fracture, Beijing China
3. Edwards P, O'Conner A, Ramulu M (2013) Electron beam additive manufacturing of titanium components: properties and performance. J Manuf Sci 135
4. Van Hooreweder B, Moens D, Boonen R, Kruth J-P, Sas P (2012) Analysis of fracture toughness and crack propagation of Ti6Al4V produced by selective laser melting. Adv Eng Mater 14(1–2)
5. Zhang X, Martina F, Dingi J, Wang X, Williams SW (2016) Fracture toughness and fatigue crack growth rate properties in wire+arc additive manufactured Ti-6Al-4V. Fatigue Frac Engng Mater Struct 00:1–14
6. Cain V, Thijs L, Van Humbeeck J, Van Hooreweder B, Knutsen R (2015) Crack propagation and fracture toughness of Ti6Al4V alloy produced by selective laser melting. Addit Manuf 5:68–76
7. Edwards P, Ramulu M (2015) Effect of build direction on the fracture toughness and fatigue crack growth in selective laser melted Ti-6Al-4V. Fatigue Frac Engng Mater Struct 38:1228–1236
8. Seifi M, Dahar M, Aman R, Harrysson O, Beuth J, Lewandowski J (2015) Evaluation of orientation dependence of fracture toughness and fatigue crack propagation behaviour of as-deposited ARCAM EBM Ti-6Al-4V. JOM 67(3):597–607
9. API Specification 5L "specification for line pipe", Forty-fifth Edition, Includes Errata (2015), standard by American Petroleum Institute
10. Yadollahi A., Shamsaei N., Thompson S. and Seely D., "Effects of process time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel
11. Meissner A, Erdelen-Peppler, M and Schmidt T, 'Impact of reel-laying on mechanical pipeline properties investigated by full- and small-scale reeling simulations' in Proceedings of the nineteenth (2009) international offshore and polar engineering conference, ISOPE-2009, Osaka, Japan, June 21–26, 2009
12. Wang Y Y, Liu M, Stephens M, Petersen R and Horsley D, 'Recent development in strain-based design in North America', in Proceedings of the 19th international offshore and polar engineering conference, ISOPE 2009, Osaka, Japan, 21–26 July 2009
13. Baek J-H, Kim Y-P, Kim W-S (2000) Effect of orbital automatic welding on the weld metal mechanical properties in API 5L X65 natural gas transmission pipe. In: Proceedings of the international pipeline conference – volume 1. ASME
14. Read DT, McHenry HI, Steinmeyer PA, Thomas RD (Apr.1980) Metallurgical factors affecting the toughness of 316L SMA weldments at cryogenic temperatures. Weld J 59(4):104s–113s
15. API 579-1/ASME FFS-1- 'fitness-for service', 2016
16. Picker C (1983) The fracture toughness of type 316 steel and weld metal. Risley Nuclear Laboratories, UKAEA, Risley
17. Huthmann A (1994) Fracture toughness round robin on type 316L mod. steel in a thermally aged condition. nuclear science and technology, European Commission
19. Khor W, Moore P, Pisarski HG, Haslett M, Brown CJ (2016) Measurement and prediction of CTOD in austenitic stainless steel. Fatigue Fract Eng Mater Struct 39:1433–1442
20. Lincoln Electric website consumables specifications: http://www.lincolnelectric.com/en-gb/consumables/Pages/consumables.aspx
21. BS 7910:2013+A1:2015, "Guide to methods for assessing the acceptability of flaws in metallic structures", British Standards Institution, 2015

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