

Fatigue strengthening of damaged steel members using wire arc additive manufacturing

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ABSTRACT

In this study, a directed energy deposition (DED) process called wire arc additive manufacturing (WAAM) is employed for the fatigue strengthening of damaged steel members. Three steel specimens with central cracks were tested under a high-cycle fatigue loading (HCF) regime: (1) the reference specimen; (2) the WAAM-repaired specimen with an as-deposited profile, and (3) the WAAM-repaired specimen machined to reduce stress concentration factors (SCF). The corresponding finite element (FE) simulation of the WAAM process was calibrated using static experimental results, which revealed the main mechanism. The process was found to introduce compressive residual stresses at the crack tip owing to the thermal contraction of the repair. The FE results also revealed that stress concentration exists at the root of the as-deposited WAAM; this stress concentration can be mitigated by machining the WAAM to a pyramid-like shape. The fractography analysis indicated that the cracks were initiated at the WAAM-steel interface, and microscopic observations revealed that the microcracks were arrested by the porosities in the melted interface. The results of this pioneering study suggest that WAAM repair is a promising technique for combating fatigue damage in steel structures.

1. Introduction

Steel structures under cyclic loading, for example, steel bridges and steel cranes, are vulnerable to fatigue damage, which degrades their structural performance and integrity. Several techniques exist to combat the fatigue problems of steel structures by reducing the local stress concentration at the crack tip, typically via: (1) the introduction of extra stress-transferring paths and (2) the introduction of a compression stress field at the cracked section. Impact crack-closure retrofit (ICR) treatment [1,2] uses tools with needle heads to repetitively punch fatigue-sensitive locations to introduce local compression and bridge existing cracks. CFRP strengthening [3–5] employs carbon fiber reinforced polymer (CFRP) materials (sheets or strips) spanning over the crack, introducing extra load-carrying paths, resulting in reduced stress concentration. When a prestressed CFRP material is used, fatigue cracks can be fully arrested owing to the compressive stress field introduced at the crack tip, which drastically reduces the stress intensity factor (SIF) [4,6].

Strengthening using an iron-based shape memory alloy (Fe-SMA) [7] shares similar strengthening concepts with CFRP strengthening, namely extra stress transferring paths and introducing compression via prestress, although the mechanisms of prestressing and the strengthening process are different. The prestress of the Fe-SMA is applied by heating the pretrained Fe-SMA strip and exploiting the shape memory effect [8]. Both of these strengthening methods have been applied in practical situations, such as bridge strengthening [9–12].

Apart from the above-mentioned techniques, weld repair [13,14] is a traditional but effective method that has been successfully applied in various fields, such as petrochemical and refinery plants. The general process involves removing the top layer of the old or damaged steel by grinding and welding, using different strategies. Before and after welding, pre- and post-heating treatments are commonly used to minimize the residual stress and formation of new cracks. Drilling holes and inserting pins near an existing crack have also confirmed to be effective methods for redirecting the crack path and retarding its propagation [15]. This system introduces compressive stresses and reduces the stress

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Nomenclature

ICR	Impact crack-closure retrofit
CFRP	Carbon fiber reinforced polymer
Fe-SMA	Iron-based shape memory alloy
WAAM	Wire arc additive manufacturing
AM	Additive manufacturing
DED	Direct energy deposition
FE	Finite elements
IS	Inherent strain technique
EDM	Electrical discharge machining
PTA	Plasma transferred arc welding
MIG	Metal inert gas
MAG	Metal active gas

TIG	Tungsten inert gas
CMT	Cold metal transfer
σ_Y	Yield strength
σ_{UTS}	Ultimate tensile strength
DIC	Digital image correlation
$\Delta\sigma$	Fatigue stress amplitude
ν	Poisson ratio
HAZ	Heat affected zone
SIF or K_I	Mode I stress intensity factor
E	Young's modulus
$a-N$	Half-crack length vs. number of cycles
OM	Optical microscopy
SEM	Scanning electron microscopy

concentration around the crack tip as it becomes blunt.

This study aimed to explore the use of additive manufacturing (AM) as a strengthening strategy. AM, particularly metal 3D-printing, is a recent technology used for the fabrication of components. This technique has received wide attention over the past few years owing to its advantages, such as design freedom and minimization of material usage and waste. The three different AM methods for fabricating metals, as presented in ISO/ASTM 52900, include powder bed fusion, direct energy deposition (DED), and sheet lamination methods, among which the powder bed fusion technique has the highest accuracy in manufacturing [16,17]. However, it has a low deposition rate and some size limitations. Furthermore, the equipment and feedstock materials are relatively expensive, which has resulted in limited applications in civil engineering.

Alternatively, wire arc additive manufacturing (WAAM), which is a DED technology, offers a high deposition rate, rapid processing time, high density, flexibility in materials, and most importantly, a lower overall cost compared to other metal AM techniques. WAAM combines standard wire-based welding processes, such as plasma transferred arc welding (PTA), metal inert gas (MIG), and tungsten inert gas (TIG), as the heat input and wire as a filler material [18]. It is suitable for

medium- to large-scale components with low-to-medium geometric complexity. It allows for high deposition rates and virtually no limitations on part size for creating shapes [17,19]. Because welding torches are relatively small and can be easily placed on industrial robots, large parts can be fabricated if they are within the capability of the robot. Consequently, WAAM is being increasingly used in industries such as aerospace, transportation, and oil and gas owing to its unique advantages in terms of overall cost savings and speed [20,21]. The use of WAAM in the construction industry was also investigated with extensive testing at material level [22] and structural level [23–25]. Some recent studies have demonstrated the possibility of WAAM repair of damaged metallic materials, such as cast iron [26] and monel alloys [27]. However, the most recent research and production in WAAM is focused on expensive high-spec materials, and very few studies have focused on WAAM repairs and crack repairs.

In this study, the WAAM technique was employed to repair damaged steel plates to enhance their fatigue performance. The WAAM repair process involves depositing melted steel wire onto the target area of a steel substrate, followed by a cooling process. Two main benefits will be discussed: (1) the local stress is reduced because of an increased net cross-section (deposited steel material) and (2) a compressive stress is

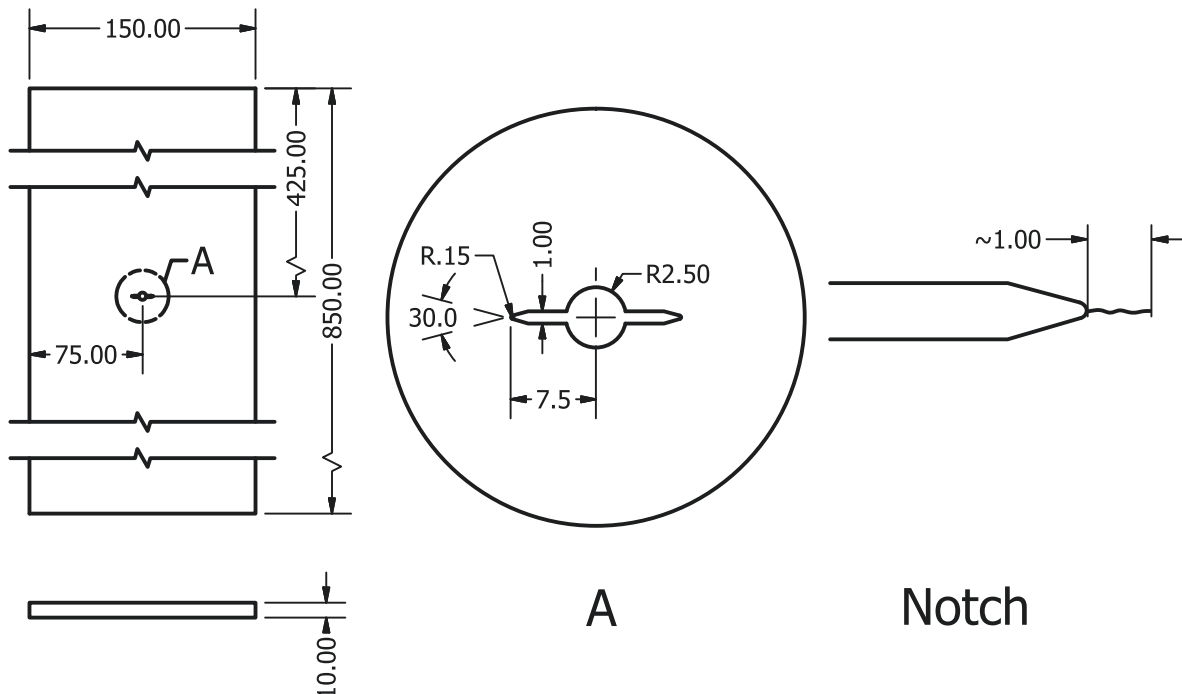


Fig. 1. Specimen configuration prior to strengthening.

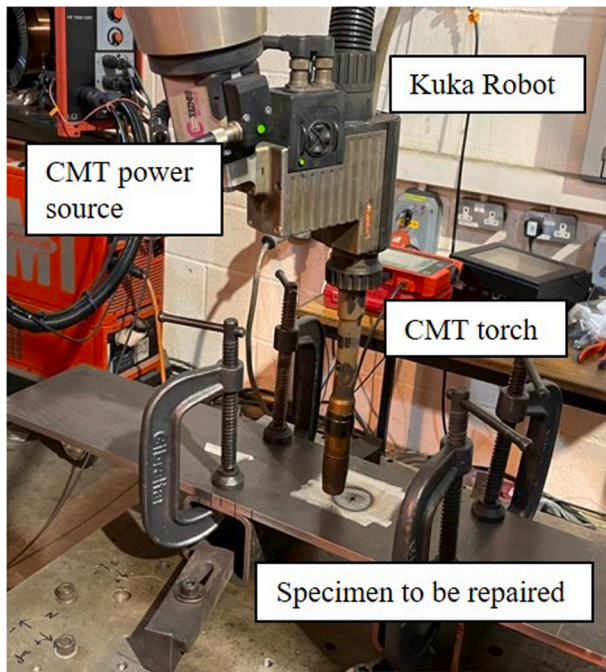


Fig. 2. Experimental setup for the WAAM-repaired specimens.

Table 1

Process parameters.

Process	CMT
Synergic line	CMT 1355 with 1.0 mm wire
Shield Gas	Argon Shield Heavy, 78% Ar, 20% CO ₂ , 2% O ₂
Wire	ER70S-6
Average Current	148 A
Average voltage	13.0 V
Arc length correction	0%
Wire feed speed	5.8 m/min
Travel speed	10 mm/s
Bead Width	4.8 mm
Total beads	9
Bead length	30 mm
Layer height	2 mm
In process temperature	20 °C

generated at the crack tip during the cooling process, provided that the deposition path is well designed. To examine the efficacy of the WAAM repair, three fatigue tests were conducted: (1) a reference plate without any repair/strengthening; (2) a WAAM-repaired plate with an as-deposited profile, and (3) a hybrid manufacturing WAAM-repaired plate, machined to a pyramid profile to reduce the stress concentration at the deposition root. Finite element (FE) simulations of these three plates were conducted to assist in the analysis of the experimental results and to understand the mechanisms of WAAM repair. A microscopic analysis of the crack surface was conducted to determine the fatigue crack initiation mechanisms.

2. Materials and method

To investigate the efficacy of the proposed strengthening system, one static test and two fatigue tests were conducted on WAAM-repaired steel plates. Steel plates with the configurations used in previous studies

Table 2

Chemical composition of the WAAM wires (wt.-%).

	C	Mn	Cr	Si	Ni	Mo	S	P	Cu	V
ER70S-6	0.09	<1.60	0.05	0.09	0.05	0.05	0.007	0.007	0.20	0.05

[4,7,28] were adopted, including a central notch cut by electrical discharge machining (EDM), as presented in Fig. 1. The plates were made of mild steel grade S355J2 + N with a yield strength of 421 MPa, ultimate tensile strength of 526 MPa, and elastic modulus of 205 GPa [4].

2.1. Precracking

Prior to strengthening, the steel plates were precracked to create a sharp crack at the notch tip, as shown in Fig. 1. This process aims to eliminate the residual stress generated at the notch tip during the EDM process to create the initial notch. Each plate was loaded for 100,000 cycles with $\Delta\sigma = 75\text{ MPa}$ and an R-ratio of 0.2 to propagate the half-crack length from 7.5 to approximately 8.5 mm. This 1 mm sharp pre-crack length was selected following the procedure described in the previous works [4] and based on ASTM standard E647-15 [29].

2.2. WAAM process and material

After precracking the steel plates, WAAM deposition of the molten metal onto the notch region was performed. The WAAM process used was cold metal transfer (CMT), a modified gas metal arc welding process based on the short-circuiting transfer process developed by Fronius in Austria in 2004 [30]. The CMT process is characterized by a relatively low heat input, low spatter, and a medium deposition rate. Another significant advantage of CMT is the coaxial wire with the torch, which provides a more straightforward tool path design and therefore more flexibility in repairs and deposition [31–33]. Owing to these excellent characteristics, distortion and residual stress in the final product are reduced, thereby enabling complex toolpath repairs. Therefore, this process was identified as ideal for fatigue strengthening of cracked steel plates.

Fig. 2 shows the WAAM deposition setup, which includes a Kuka 6-axis industrial robot with an MTB500 CMT torch and Fronius power supply. The deposition was conducted at a constant starting temperature for each layer and alternated the deposition sides between the top and bottom surfaces every layer to reduce the potential distortion of the specimens. The oxidized layer in the deposition areas of the steel plates was removed by grinding to enhance the bonding between the WAAM-deposited material and original plate. A series of beads on plates were initially deposited in order to select the print process parameters to produce a bead width similar to the notch size with a contact angle of less than 80 degrees (between the bead and the plate) to avoid lack of fusion defects and porosities. The in-process temperature is chosen to be the room temperature to provide the maximum strength. The final process parameters are listed in Table 1.

The wire used for the WAAM deposition in this study was ER70S-6 with a diameter of 1 mm. The detailed chemical composition and mechanical properties of the WAAM wire and deposit [34] are listed in Table 2 and Table 3. The deposition strategy employed in the current study was oscillation deposition with a 33% overlap with the previous bead, as shown in Fig. 3.

Table 3

Mechanical properties of the WAAM wires and deposit (wt.-%).

	Wire datasheet	Horizontal	Vertical
σ_Y (MPa)	450	390	365
σ_{UTS} (MPa)	540	522	518
E (GPa)	–	209	221

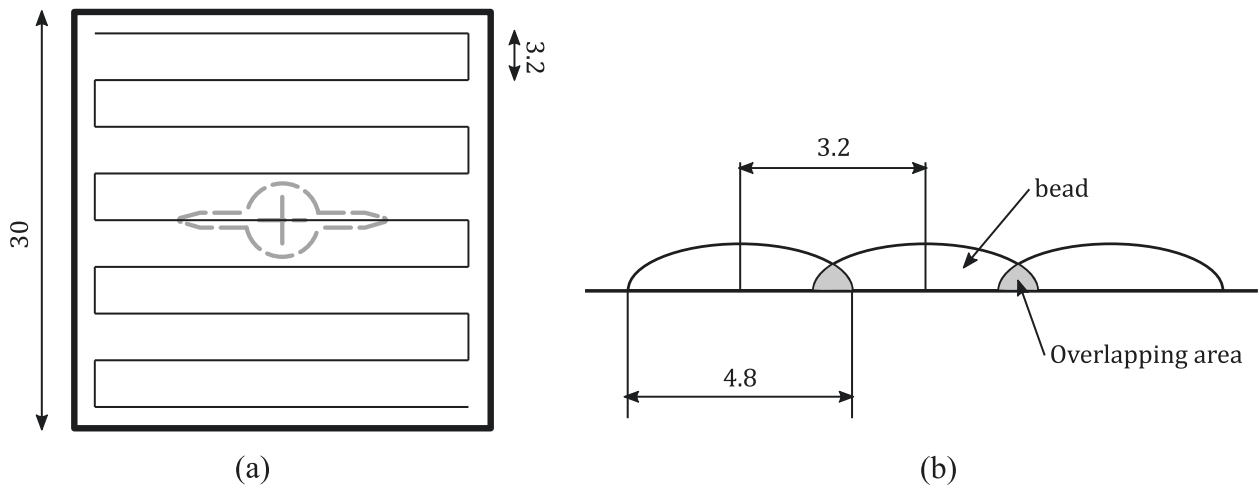
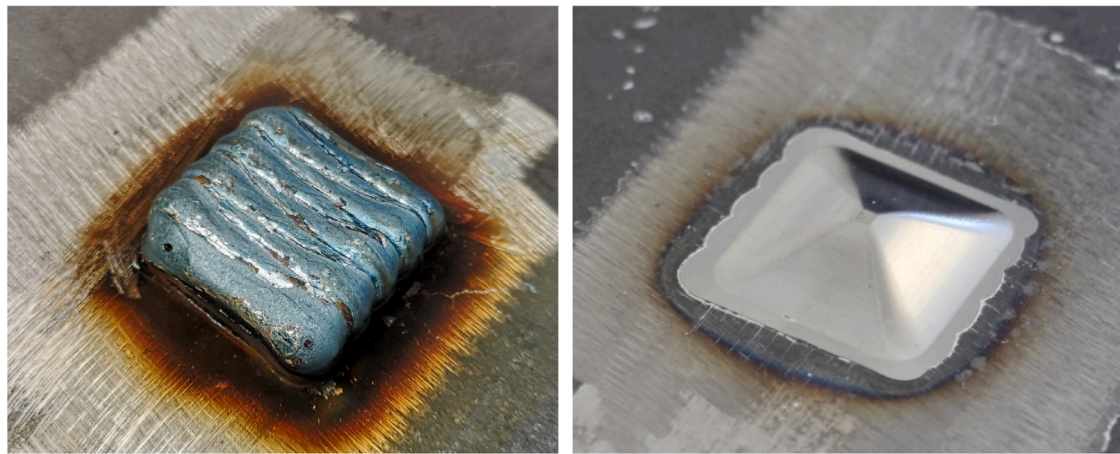


Fig. 3. (a) Oscillation deposition of the WAAM repair (in mm). (b) Deposition overlap with previous bead in WAAM repair.



(a) As-deposited WAAM

(b) Machined WAAM

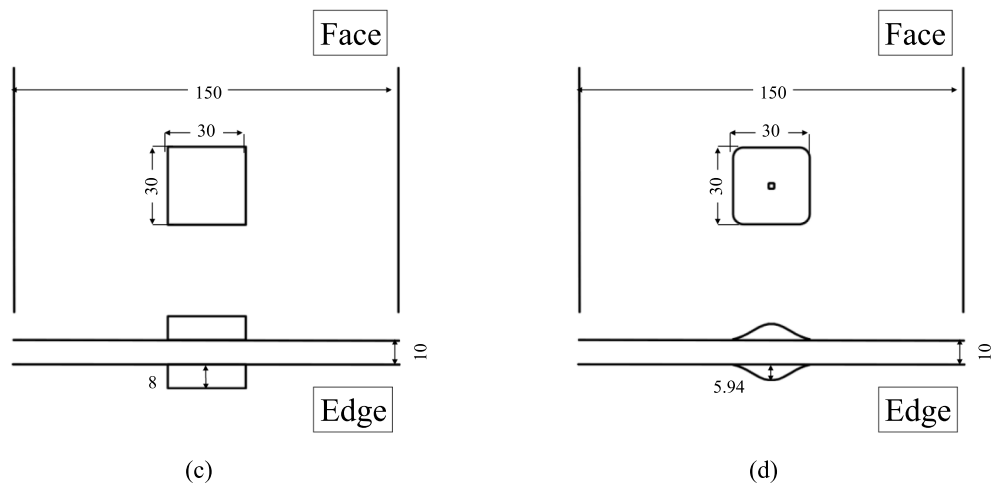


Fig. 4. Geometrical properties of the WAAM repair in (a) and (c) as-deposited specimen and (b) and (d) machined specimen (in mm).

The repairs were square patches with an area of 30 mm $\times$ 30 mm and a thickness of 8 mm deposited on each side of the plate. The as-deposited WAAM is shown in Fig. 4(a) and 4(c). Because the deposition process is similar to welding, which may potentially induce new fatigue problems due to stress concentration, one of the repaired specimens was machined to a pyramid-like shape (Fig. 4(b) and 4(d)) to reduce the stress

concentrations at the interface between the steel substrate and WAAM deposit.

2.3. Static and fatigue tests

To investigate the strengthening efficacy, fatigue tests were

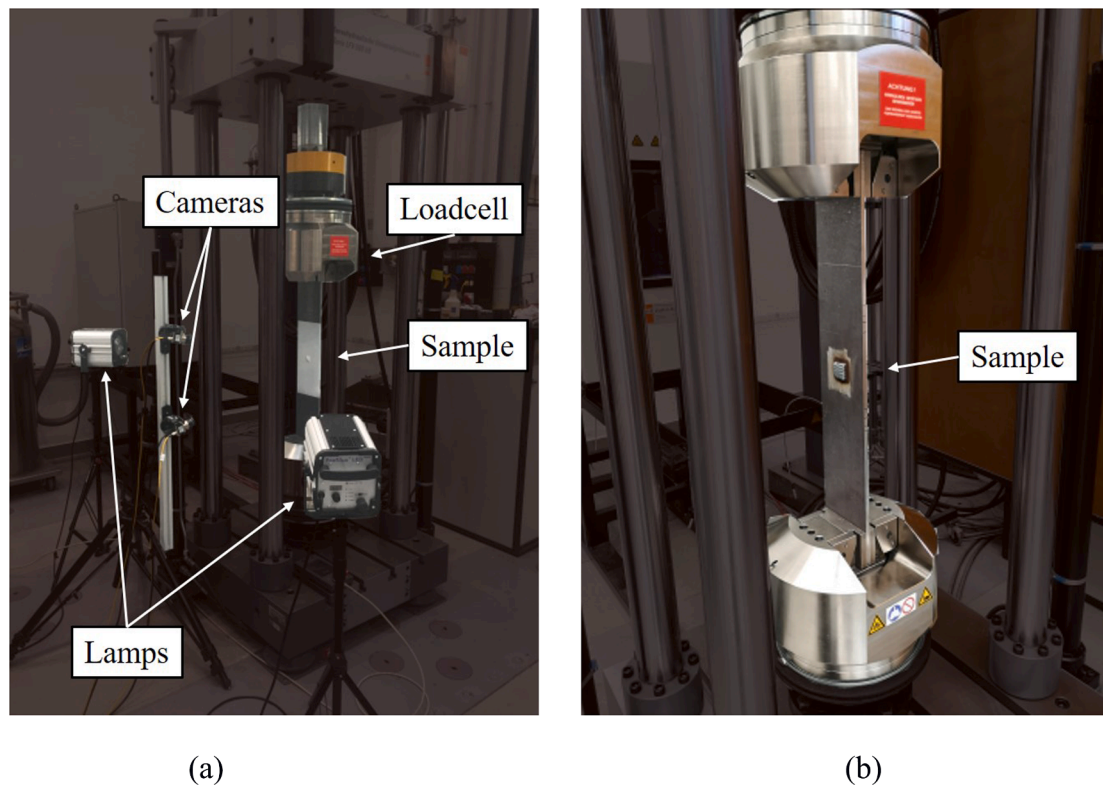


Fig. 5. Experimental setups. (a) Static test setup with 3D DIC measurements, (b) Fatigue test setup, with the as-deposited specimen demonstrated.

conducted on all the specimens in a uniaxial servo-hydraulic universal testing machine (Walter & Bai) with a maximum capacity of 500 kN, as shown in Fig. 5 (b). Prior to the fatigue tests, the machined specimen was tested under a static load to better understand the mechanism of WAAM repair. The plate with the machined WAAM repair was tensioned to 100 kN (nominal tensile stress was 66.7 MPa, as plotted in Fig. 6 (a) in black) under a load-control regime and then unloaded to zero force without any expected damage to the plate. The loading rate was 0.5 kN/s, the sampling rate was 5 Hz, and a 3D digital image correlation (DIC) technique was utilized to measure the full-field strain, with an image acquisition

rate of 1 Hz. The test and measurement setups are shown in Fig. 5 (a).

Fatigue tests on the two WAAM-repaired plates were conducted under a load control regime at a frequency of 10 Hz. The maximum and minimum tensile stresses on the nominal cross-section were 93.75 and 18.75 MPa, respectively, shown in Fig. 6 (b) in blue. The corresponding stress range (difference between the maximum and minimum stresses) was 75 MPa with a stress ratio (R-ratio, minimum stress over maximum stress) of 0.2. To track the crack length and the corresponding fatigue loading cycles, a beach-marking loading regime (see Fig. 6 (b) in red) with an increased R-ratio of 0.6, which leads to lower stress range and slower crack propagation rate, was used; the maximum nominal stress was kept unchanged, while the minimum nominal stress became 56.25 MPa. The fatigue tests were conducted by repeating the fatigue loading blocks. In each loading block, 25,000 beach-marking loading cycles were applied after every 50,000 effective cycles. Only the number of effective cycles is reported.

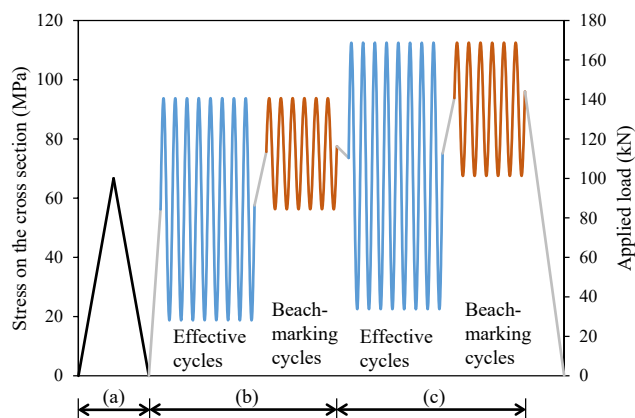


Fig. 6. Loading regime: (a) static loading to 100 kN followed by unloading (only applied to the plate with machined WAAM repair); (b) fatigue loading block applied to all plates; (c) fatigue loading block with the increased load level (only applied to the plate with machined WAAM repair after 6 million effective cycles in loading block (b)). The cyclic loading with the high stress range (in blue) represents the effective loading with 50,000 cycles, whereas the case with low stress range (in red) refers to the beach-marking loading with 25,000 cycles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4. Fractography specimen preparation

After the fatigue tests, the fatigue-fractured surfaces were observed at the macro- and micro-levels using optical microscopy (OM) and scanning electron microscopy (SEM), respectively. For OM and SEM observations, the fractured surfaces were cleaned to eliminate corrosive products or contaminants attached to the surfaces. The cut specimens containing the cracks and WAAM repair were placed in an ultrasonic bath for 10 min. The ultrasonic tank was partially filled with water, and the specimens were placed in a beaker filled with a cleaning organic solution (ethanol). Furthermore, specimens for OM and SEM observations were ground, polished, and etched with a solution of H_2O_2 (35%), HNO_3 (65%), and HCl (32%), in the ratio of 7/30/9 by volume.

2.5. FE simulation of WAAM repair

To gain a deeper insight into the mechanism of WAAM repair, three plates: reference plate, as-deposited WAAM-repaired, and machined

WAAM-repaired plates were modeled using the commercial FE software ABAQUS 2017 [35]. Residual stresses and distortions are the most critical issues in parts fabricated via 3D printing. Two finite element (FE)-based methods can be used to predict residual stresses and distortions: (1) a coupled thermo-elastic-plastic analysis, in which the welding process is considered as a transient nonlinear problem [36,37] and (2) the inherent strain method, in which the distortion and residual stress are predicted by elastic analysis using the inherent strain as the initial strain [38–42]. The inherent strain (IS) method significantly enhances the computational efficiency, indicating excellent potential for residual stress prediction compared to complex thermo-mechanical analysis. The technique was applied and validated through simulations of large welded structures [39,43–47], which have a process similar to that of WAAM repair. In addition, in the IS method, temperature-dependent material properties are not necessary, and only the material properties and Poisson's ratio at room temperature are sufficient to set up an analysis [48]. The IS technique was employed in this study owing to the above-mentioned advantages.

2.5.1. Static simulation

In the FE models, the specimen geometries, dimensions, and mechanical properties were defined as those used in the experiments. To create a machined WAAM shape, as depicted in Fig. 4(b) and 4(d), the Rhinoceros 3D and Grasshopper [49] were employed. The steel plates and WAAM parts were modeled as isotropic elastoplastic materials, with properties adopted from Hosseini et al. [4] and Ermakova et al., respectively [30]. The Poisson ratio ν was defined as 0.3 for all materials.

Owing to geometrical symmetry, only one-eighth of the specimens were modeled, as shown in Fig. 7, and the corresponding boundary conditions were applied to the symmetry planes. Another boundary condition was enforced to simulate the clamping system in the repaired specimens during WAAM deposition. A set of nodes placed appropriately, according to Fig. 7 was pinned during the deposition simulation

and then set free. To simulate the precrack, an area with a length of 1 mm behind the crack tip was set free (without defining any boundary conditions). Given that the main interest of this study has been placed on the use of WAAM to arrest fatigue cracks, only the initial crack length was considered in the simulations. Finally, a uniformly distributed tensile pressure, σ , as shown in Fig. 7, was applied at one end of the steel plate. The interfaces between WAAM and the steel plate were modeled as “ties.”

Most elements in the steel plate and the as-deposited WAAM elements were defined as C3D8R elements, whereas C3D6 elements were used to model the wedge elements near the crack tip with a very fine radial mesh, as depicted in Fig. 7. In addition, the machined WAAM details were modeled using a combination of C3D4 and C3D8R elements. After a convergence analysis, the element size for both the as-deposited and machined WAAM elements was 0.5 mm.

2.5.2. Inherent strain technique

In the IS method, a certain value of strain should be defined in all directions per activation layer to simulate thermal contraction during the cooling of the deposited WAAM. In practice, this is modeled by assigning an isotropic coefficient of thermal expansion to a specific material section in the deposition direction. A unity temperature increase was then applied to induce isotropic compressive strain in this section. This strain is the inherent strain and, as a first estimation, the thermal expansion coefficient is set such that the inherent strain equals the yield strain (σ_Y/E) [48,50].

The correct inherent strain values were calibrated with the steel plate tested statically and measured by DIC, as described in Section 2.3, and FE modeling considering purely elastic properties. A comparison between FE and DIC is presented in Section 3.1. A more detailed theory underpinning this IS technique can be found in the literature [43].

The WAAM simulation process using the IS technique is as follows: Both the as-deposited and machined WAAM parts were discretized into different layers. All layers, namely the elements of the bead, were

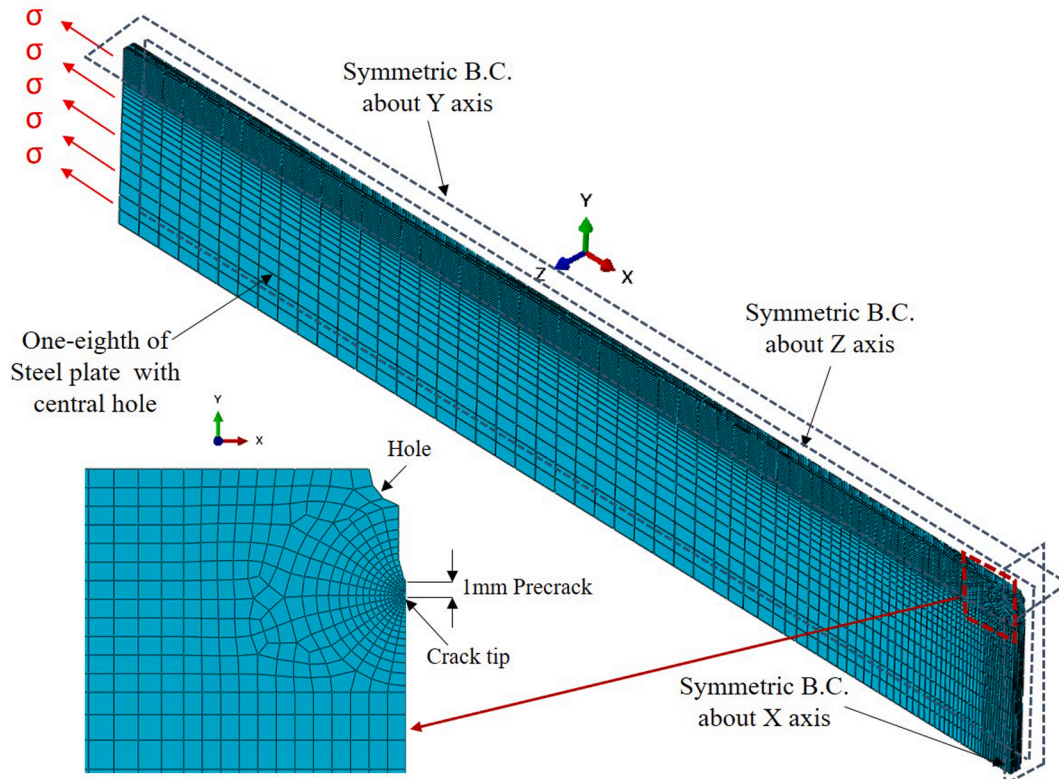


Fig. 7. Details of the FEM for the reference specimen created in ABAQUS.

deactivated in the first step. The deposition process was modeled by activating each layer corresponding to the deposition. The element birth technique [51] was used to realize deactivation and reactivation. In both the as-deposited and machined WAAM models, one layer in the steel plate was considered to represent the heat-affected zone (HAZ). After the simulation of WAAM deposition, the clamping boundary condition was removed and an external load was applied.

2.5.3. Stress intensity factors

To characterize the state of the crack after the WAAM repair, the SIF was calculated using the J-integral. The J-integral allows for the estimation of the energy release rate associated with a crack enclosed in the

integration surface. The path independence property of the J-integral causes the J-value computed from expanding contours (Fig. 9) to converge to a certain value, as shown in Fig. 10(a). Owing to the 3-dimensionality of the problem, the crack front is a line and the J-integral value varies along this line through the thickness of the steel plate. Fig. 10(b) shows the computed J-integral along the crack front of the reference plate. For simplicity, the average value was adopted. In the computation of the SIF, a positive J value leads to a positive SIF, whereas a negative J value corresponds to a negative SIF.

To validate the FE models, the SIF at the crack tip of the reference plate obtained from the J-integral was compared with that estimated from the analytical Equation (1) [52], where a and w are the half crack length (including the precrack) and width of the steel plate, respectively, as shown in Fig. 6. Table 4 shows a good match between the SIFs estimated using the two methods, with an error of only 0.8%.

$$K_I = \sigma \cdot \sqrt{\pi a \sec\left(\frac{\pi a}{w}\right)} \quad (1)$$

3. Results and discussion

The main results of this study are discussed in detail in this section. First, the surface strain of the machined WAAM-repaired plate measured by DIC is compared with that obtained from the FE model to calibrate the IS parameters. Subsequently, the fatigue tests results are illustrated via crack propagation and the corresponding fatigue life. The fatigue-fractured surface is examined using microscopy to better understand the failure mechanism. Further, FE models of the two WAAM-repaired specimens are employed to qualitatively explain the mechanism of WAAM repair. Finally, a comparison with the other strengthening methods mentioned in this work is proposed.

3.1. Results of static test and strain measurement

As mentioned in Section 2.3, the machined plate was statically loaded prior to the fatigue loading. The full-field strain was measured using 3D DIC, and the effect of the repair on its surroundings was evaluated. Fig. 11(a) displays the four lines on the specimen surface, from which the strains were extracted for the analysis: a transverse centerline (L0) that passes through the middle of the deposited strengthening; reference line (L1) located 60 mm away from the

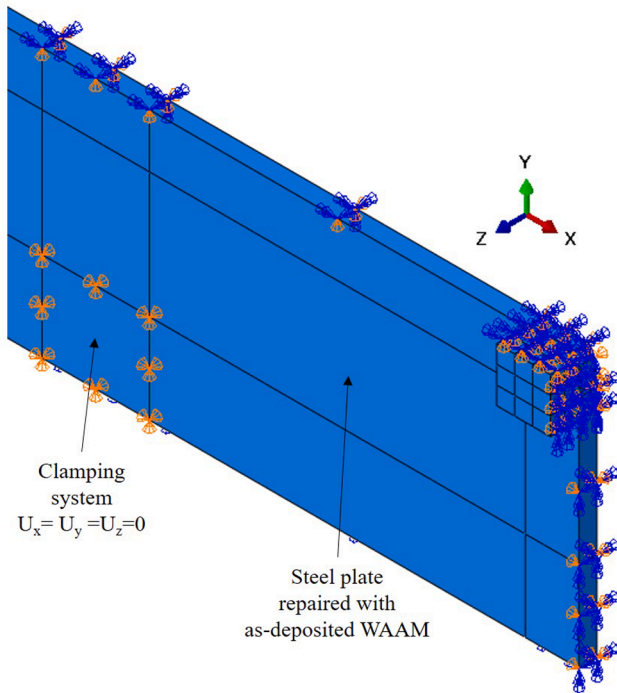


Fig. 8. Applied boundary conditions during the WAAM process.

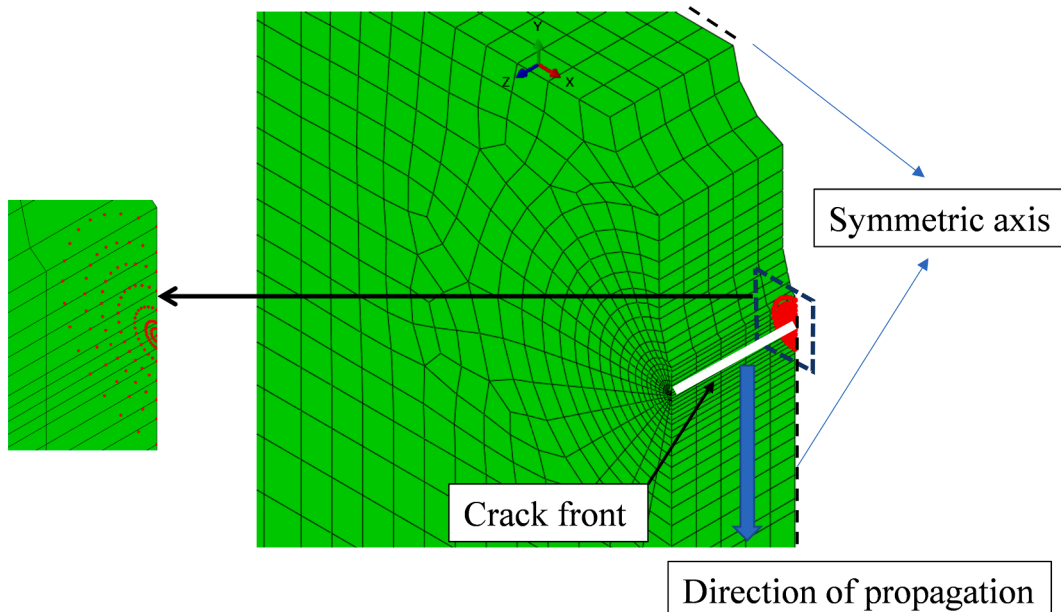


Fig. 9. Crack front and the J-integral contour locations.

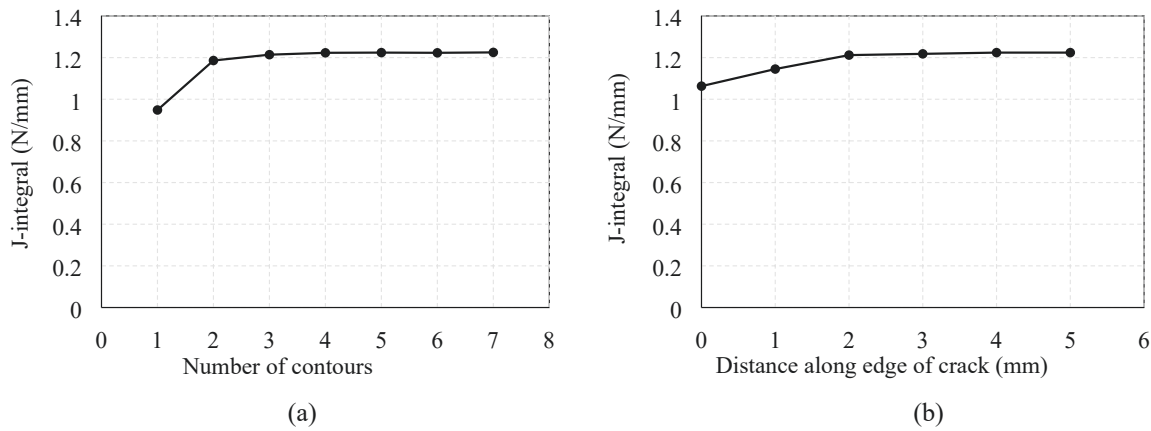


Fig. 10. (a) J-integral value along successive contours. (b) Variation of the J-integral value along the crack; 5 mm is the middle of the specimen.

Table 4

SIF comparison.

K_I Analytical ($\text{N/mm}^{3/2}$)	K_I FEM ($\text{N/mm}^{3/2}$)	Error (%)
488.24	492.04	0.8

centerline; secondary lengthwise centerline (L3), and a lengthwise reference (L2) 18.5 mm away from L3. The reference lines were placed outside the range of influence of the repair and such that the noise to signal ratio was the lowest along the line as visually estimated on the full-field strain contour map.

To reduce the effect of the DIC noise, the strain profile was filtered in space and time using a bi-dimensional Gaussian filtering kernel. This reduced fluctuations and clarified the features of the strain profiles. All the displayed strain profiles were measured at the end of the static loading of the machined plate, with a tensile force of 96.47 kN. Note that the strain measured by DIC only contained the deformation due to mechanical loading, and the residual deformation resulting from the WAAM process was not measured.

The strain in the loading direction along L0 is shown in Fig. 11(b) along with the surface geometry, and that along L1 is shown in Fig. 11(c). As seen from the figures, the locally increased cross-section reduces strain level. This effect is localized and does not significantly affect the surrounding strain field as the strain reaches the same level as the remote strain 20 mm away from the repair root. This is likely an over-estimation because filtering has the effect of flattening and widening strain peaks. A similar conclusion can be drawn from Fig. 11(e), where the effect of repair is quickly reduced.

Fig. 11 shows a comparison between the experimentally measured strain using DIC and the strain computed using the FE model. As the DIC only measures the relative deformation caused by the mechanical loading, the depicted FE strain only comprises the mechanically induced strain and the thermal part was subtracted for the sake of comparison. A general agreement is observed between the experimentally measured and FE-computed strains on the four lines, L0–L3. Away from the region of repair (Fig. 11(c) and 11(d)), the strain field was constant, and the measurements were consistent with the FE model. When observing the repair directly (Fig. 11(b) and 11(e)), the strains reached similar values on the repair top, which suggests that WAAM details were modeled correctly.

Fig. 11(d) reveals that the first mechanism to combat fatigue crack propagation is the introduction of extra stress-transferring paths in the form of a welded profile. Reinforcement was gradually added to the two sides of the 10 mm plate up to 5.95 mm of steel. Consequently, local thickness was enhanced by more than 100%, and the strain level in the crack section was reduced.

3.2. Results of fatigue tests

3.2.1. Fatigue crack propagation

The two repaired plates were then tested for fatigue, following the loading protocol detailed in Section 2.3. Fig. 12 shows the fatigue tests results in the form of a - N curves and half crack length vs. fatigue loading numbers for the three specimens: the reference plate and the two WAAM-repaired plates tested in the current study. To compare the efficacy of the proposed repair technique with that of conventional repair using composite materials, a specimen strengthened with bonded CFRP strips [7] was also included. Bonded strengthening with (non-prestressed) bonded CFRP strips reduces the stress intensity at the crack tip by introducing extra stress-transferring paths, thereby retarding the crack propagation speed [7]. For the CFRP-strengthened specimen, fatigue life increased from 0.94 million to 1.6 million. When the WAAM repair was used, no crack propagation was observed from the existing crack. However, a new crack was initiated at the edge of the front WAAM profile (deposition root), as shown in Fig. 13, and the final fatigue life was 2.22 million cycles. Because of the extremely slow crack propagation in the early stages, beach marks are hardly visible. The machined WAAM repair specimen is not plotted in Fig. 12 because no sign of fatigue damage was observed after six million fatigue cycles, followed by another three million cycles at a 20% increased load level.

An experimental study by Yu et al. [53] demonstrated that crack propagation rates at the same crack lengths were identical. Therefore, the a - N curve of the reference specimen was shifted by adding 1.39 million cycles to match the middle and late stages of the a - N curve of the as-deposited WAAM-repaired specimen. The two a - N curves overlap at half-crack lengths of approximately 20 mm and 2 million loading cycles. Fig. 13 shows that the semi-elliptical crack went through the plate thickness at a half-crack length (in the middle of the thickness) of approximately 20 mm. This indicates that two million loading cycles were required for fatigue crack initiation and thickness propagation. This can be divided into two steps: (1) approximately 1.39 million loading cycles (the shift of the reference specimen) were required for crack initiation and propagation until a half-crack length of 7.5 mm, and (2) approximately 0.61 million cycles were required for crack propagation from a half-crack length of 7.5 mm to 20 mm. However, the propagation of surface cracks requires more effort than a through-thickness crack with the same crack length, as a surface crack can be regarded as a through-thickness crack with extra steel material bridging the two surfaces of the crack. Therefore, step (2) would take more than 0.61 million loading cycles, whereas step (1) would have a life of no more than 1.39 million loading cycles.

For the machined specimens, neither fatigue crack propagation of the existing crack nor new crack initiation at the deposition root was observed after six million effective cycles, as shown in Fig. 6(b). The

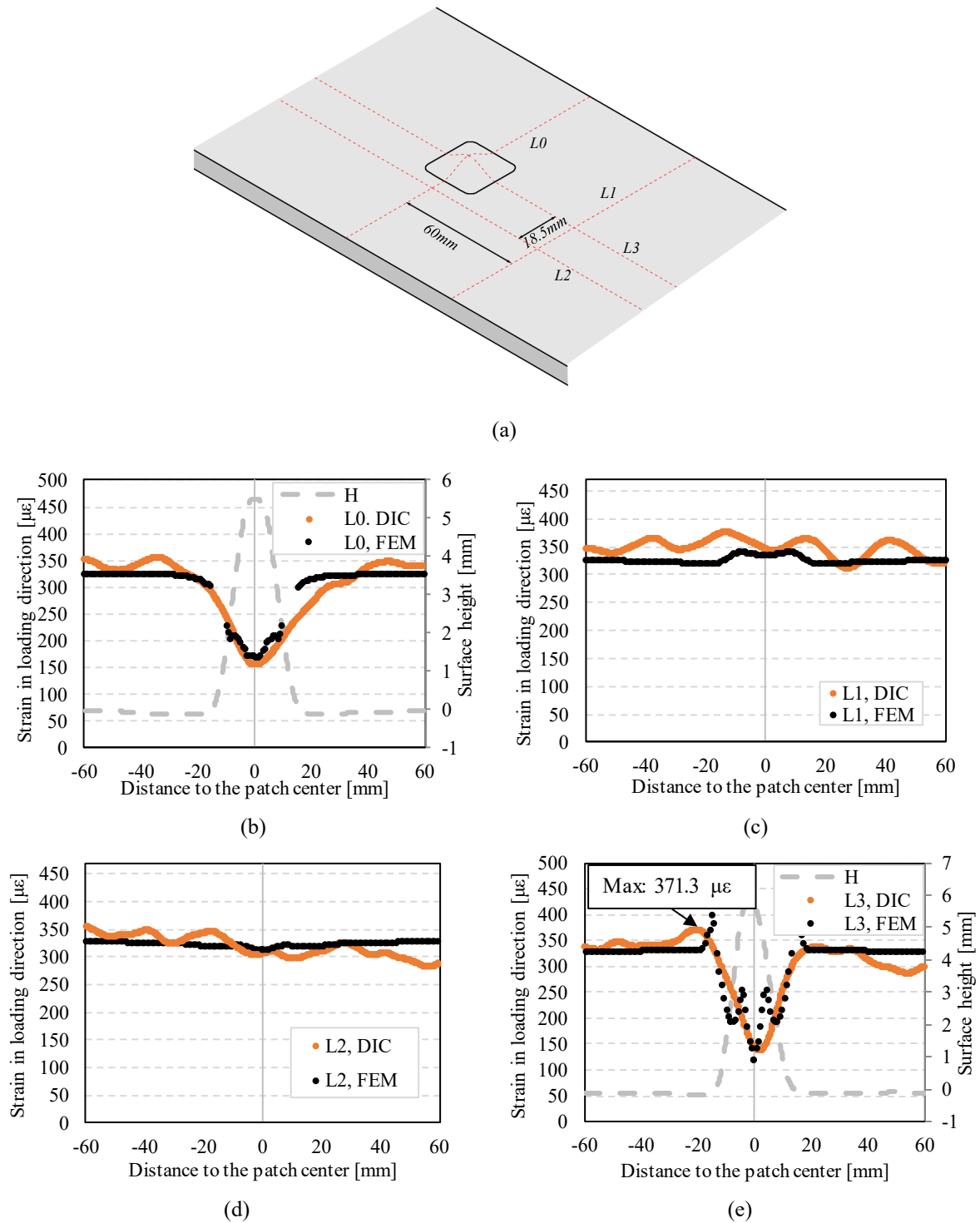


Fig. 11. DIC full-field strain measurements along relevant lines under an applied load of 96.47 kN with FE results for comparison. (a) Location of L0, L1, L2, and L3. (b) Strain profile along L0, passing through the repair. (c) Strain profile along L1, 60 mm away from the repair. (d) Strain profile along L2, 18.5 mm away from the middle of the specimen. (e) Strain profile on L3, passing through the repair.

fatigue load level was further increased by 20% (maximum and minimum nominal stress were 112.5 MPa and 22.5 MPa, respectively), and the fatigue test was run for another 3 million effective cycles, as plotted in Fig. 6(c). However, still no sign of fatigue damage was observed, as depicted by the horizontal black dashed line in Fig. 12. Thus, the propagation of the existing crack was fully arrested by the deposited WAAM profile. However, the as-deposited specimen indicates that a risk of new crack initiation exists at the interface between the WAAM profile

and steel substrate. Such a risk for the formation of new fatigue cracks can be eliminated by machining the deposited WAAM detail to provide a smooth transition by changing the deposition profile to a smoother one or by applying techniques such as interface peening.

3.2.2. Fractography results

The fatigue fracture surface of the as-deposited WAAM repair specimen was characterized at the macro- and micro-levels. Generally,

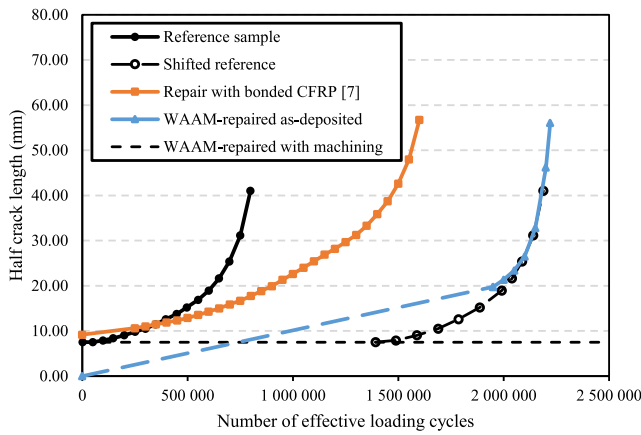


Fig. 12. Fatigue $a-N$ curves of the specimens. The curve with hollow markers is the reference curve shifted by adding 1.39 million cycles.

fatigue fractography includes several diverse areas, such as fatigue crack initiation, crack propagation, and final fracture. Fig. 14 shows the fracture morphology of the fatigue crack initiation and through-thickness propagation region (Fig. 13(a)) for the as-deposited WAAM specimen at different locations and magnifications. Fig. 14(b), 14(c), 14(d), and 14(f) show the enlarged observations of the red boxes in Fig. 14(a).

Crack nucleation is the first fracture step. The second step of crack propagation occurs when a crack nucleus is created. In this step, the major fractographic features are created. The process region is placed in front of the growing crack, and fracture mechanisms occur in this region [54]. Fig. 14(b) shows that cracks were initiated at the interface of the steel substrate and WAAM profile. A crack initiation zone was found at the edge of the front WAAM profile, which was connected to a stress concentrator and sharp corner.

Beach marks, which are also called “macroscopic striations,” stretch from side to side on a fractured surface and are long, thin, and recognizable arch-shaped lines. These lines are marked in Fig. 14(a) with red arrows and are related to the crack growth. They are mostly shaped by stops and restarts of crack propagation and load variations [54].

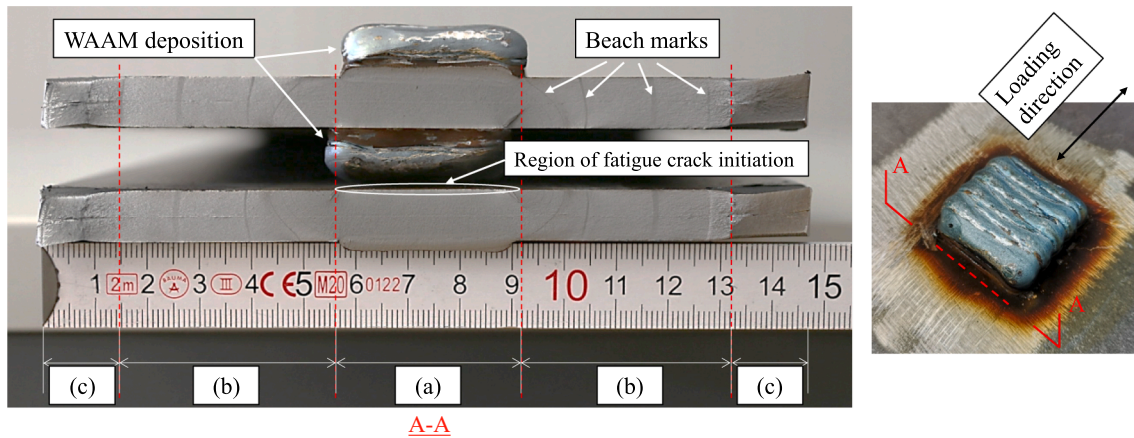


Fig. 13. Fracture surface, i.e., cross-section A-A, of the as-deposited WAAM repair specimen shows three regions: (a) fatigue crack initiation and through thickness propagation, (b) crack propagation through the width direction, and (c) sudden rupture.

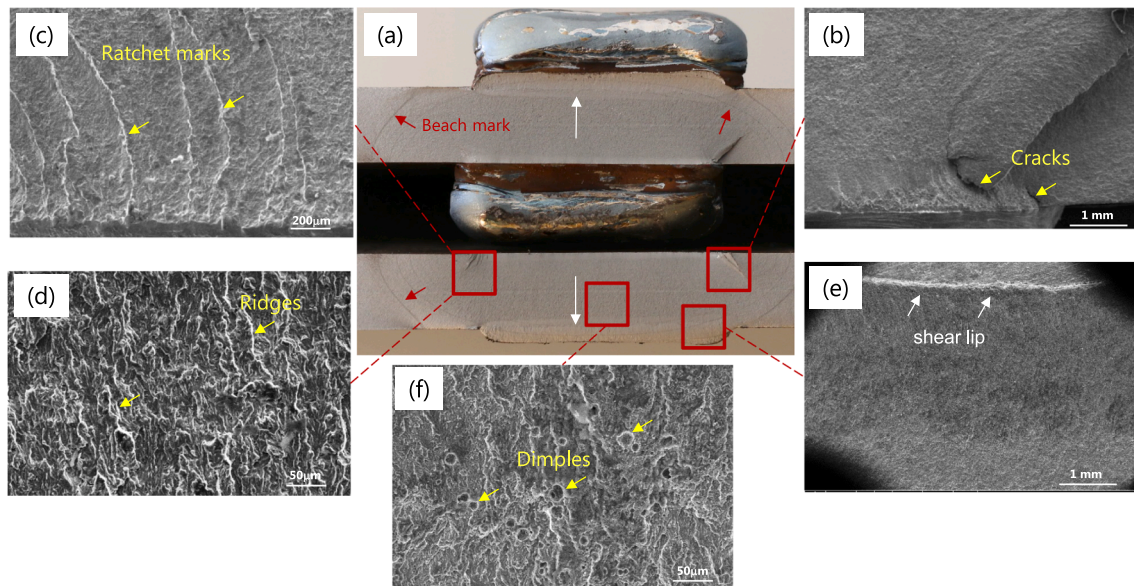


Fig. 14. Fractograph of the fracture surface of the as-deposited WAAM repaired specimen, (a), (b), (c), and (e) macro fracture morphology, (d) and (f) micro fracture morphology.

The arch source point is related to the crack initiation location, and the apparent propagation direction of the arches is related to the crack propagation direction. The white arrows in Fig. 14(a) indicate the direction of fatigue crack propagation. Fig. 14(c) and 14(d) indicate ratchet marks and ridges in the initiation region owing to the coincident nucleation of some small cracks. The ratchet marks and ridges vary at the level of the fracture surface, whose direction is parallel to the crack propagation direction. The ridges are similar to the tiny peaks created by microcracking off the major fracture plane. The source of ratchet marks is the stage shape, where several cracks, originally on somewhat dissimilar planes, connect through small secondary cracks perpendicular to the fracture plane. In addition to ratchet marks, ridges were observed (Fig. 14(d)). This indicates that a large stress concentration existed at the fatigue crack tip and that the crack propagation was susceptible to deviation under normal stress, causing a rather rough region of fatigue crack growth. Owing to the large stress concentration at the fatigue crack tip, the stress close to the crack tip exceeded the yield stress of the steel, and plastic deformation occurred, affecting the plastic region size [54].

Fig. 14(e) shows shear lips, which are keen bumps shaped on the outward edges of ductile fractured surfaces, produced by extraordinary shear stresses combined with sudden changes in the stress state towards the final fracture. The direction of the shear lip is parallel to the propagation front. The final part of the ductile fracture is a shear lip with an inclined side.

In addition, there were various ductile fracture features on the fracture surface as well as a large number of dimples of dissimilar sizes, as shown in Fig. 14(f). When the local stress at the crack tip was less than the cleavage fracture strength of the grain, many dislocation pileups were created close to the crack tip owing to the stress concentration, and microvoids nucleated in the dislocation pile-up mode. Then, the microvoids were boosted to grow via a dislocation movement around them, connecting with other microvoids, resulting in the formation of dimples [55].

Fig. 15 shows OM and SEM micrographs of the as-deposited WAAM-

repaired specimen. All images were taken from the cross-section of the WAAM-repaired specimen (Fig. 15(a)). The microstructure shown in Fig. 15(b) contains ferrite and intergranular lamellar pearlite in both the steel substrate and WAAM-deposited part. Similar ferritic-pearlitic microstructures were observed for WAAM ER 70S-6 steel by Huang et al [22]. Owing to the different carbon content of the steel substrate and WAAM part, a diverse volume fraction of pearlite was formed and observed along the grain boundaries and triple junctions of polygonal ferrite grains. In addition, the grains were stretched along the rolling direction in the steel substrate (Fig. 15(c)), whereas quasi-coaxial grains were observed in the WAAM part (Fig. 15(d)). A diffuse interface exists between the substrate and WAAM part. The OM and SEM images of the interface indicate that during the deposition of the first layer, the substrate was partially melted (Fig. 15(e)) and a diffused interface (Fig. 15(f)) with various micropores was formed, as shown in Fig. 15(g). This diffuse interface led to the initiation of cracks; however, crack propagation stopped when pores were encountered, which can be observed in the SEM images of Fig. 15(h) and 15(i). These images illustrate that the cracks were initiated at the interface and arrested by micro-porosities.

Further SEM investigation of the vertical cross-section cutouts of the machined specimen revealed that the crack length in front of the artificial notch was approximately 0.8 mm, which is lower than the expected precrack length. This confirms that no propagation occurred from the initial precrack after the WAAM repair.

3.3. FE results

The results from FE modeling elucidate the mechanisms of WAAM repair on fatigue crack retardation and arrest. Fig. 16(a) and 16(b) show the simulated longitudinal residual stresses of the as-deposited and machined WAAM specimens, respectively, prior to loading. The boundary conditions correspond to Fig. 8 without the clamping system and an applied load of 0 and 140.6kN. Tensile residual stress was generated during the cooling process after the solidification of the WAAM-deposited metal [37,56,57]. These stresses induced a balancing

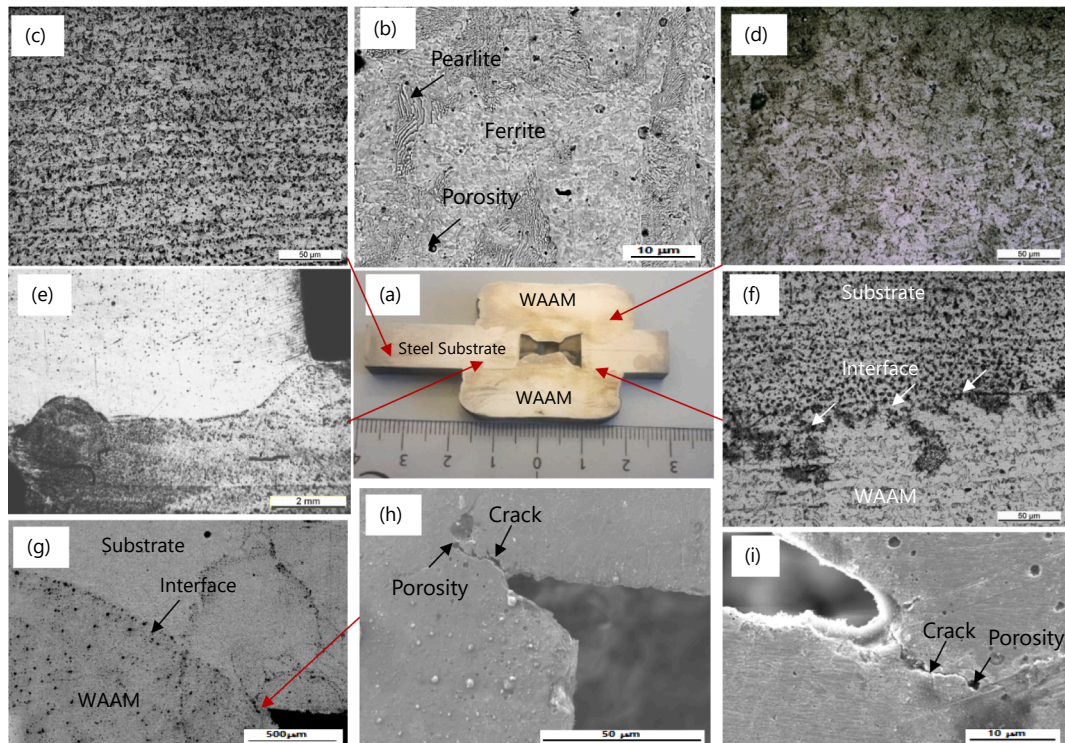


Fig. 15. Cross-sectional micrographs of as-deposited WAAM repaired specimen, (a), (c), (d), (e), and (f) are optical microscopy images and (b), (g), (h), and (i) are SEM images of steel substrate and WAAM part.

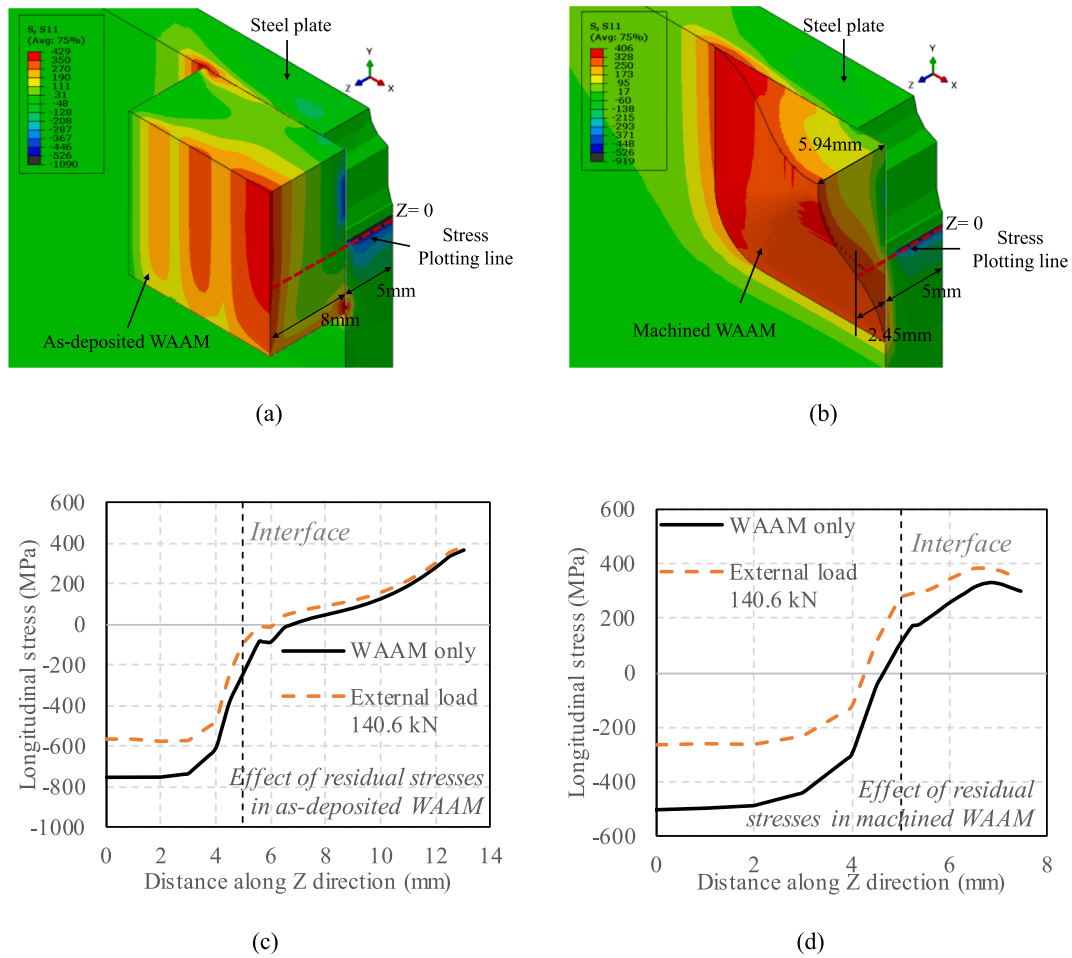


Fig. 16. Longitudinal residual due to WAAM process and total stress distribution after external loading (in MPa). (a) Residual stress in the as-deposited specimen, (b) Residual stress in the machined specimen. (c) Longitudinal stress before and after loading in the as-deposited specimen (along the line in (a)). (d) Longitudinal stress before and after loading in the machined specimen (along the line in (b)).

compressive stress in the steel plate, particularly close to the crack tip, as shown in Fig. 16(c) and 16(d), which depict the longitudinal stresses at the locations of the red dashed lines in Fig. 16(a) and 16(b) for the two WAAM-repaired plates. Similar trends could be found in [37]. The solid curves indicate the stress state prior to external loading (after applying WAAM repair), whereas the orange dashed curves depict the stress state

after applying an external load (the highest load in the fatigue regime). Owing to WAAM repair, the surroundings of the crack tip were under compression, and even with an applied external load, the crack front remained in compression. This explains the second mechanism to combat fatigue crack growth mentioned in the introduction and the reason why no crack propagation of the existing crack was observed in these two plates during fatigue tests.

Fig. 17 shows the variation of the computed SIF with applied load for the three plates. Note here that the negative values of the SIFs, although lacking physical meaning, demonstrate the absence of the crack driving force. Similar results have been reported in [4]. For the WAAM-repaired plates, crack tips were under compression during the entire fatigue loading process, with applied loads ranging from 28.1 to 168.7 kN. This further explains the fatigue crack-arrest phenomenon. The SIF at the maximum applied load, i.e., 168.7 kN, was reduced from 603 N/mm^{3/2} to -206 N/mm^{3/2}, among which approximately 63% reduction was attributed to the compressive stress via shifting the origin of the curve and 37% reduction as a result of the introduced local stiffness. Moreover, some similarities were found between WAAM repair and pre-stressed strengthening using CFRP strips [4,58] and Fe-SMA strips [7,28], as they all introduce compression in the steel plate around the crack tip and provide extra stress transfer paths.

Although the WAAM-induced compression prevented the propagation of existing crack tips, the high stress level at the welding root led to a new problem: fatigue crack initiation from the WAAM-steel interface (see Section 3.2). Fig. 18 shows the longitudinal stress in the steel plate for the as-deposited and machined WAAM specimens. A high stress level

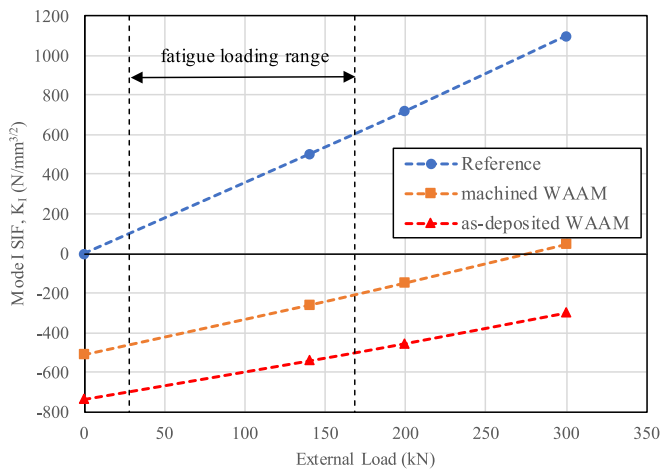


Fig. 17. Magnitudes of the stress intensity factors for the reference and repaired specimens versus the applied load.

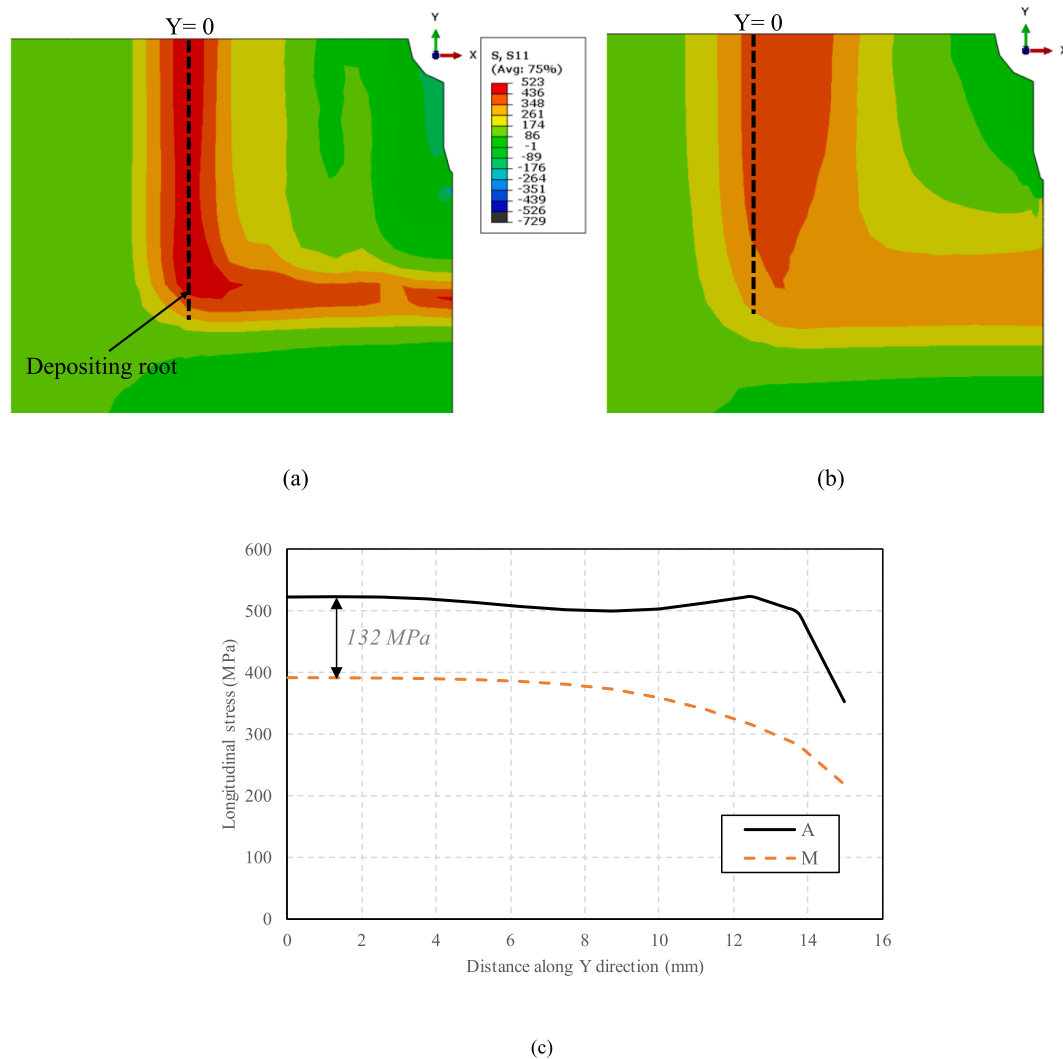


Fig. 18. Stress distribution including residual stresses in steel plate after loading (in MPa). (a) Steel plate repaired with as-deposited WAAM, (b) Steel plate repaired with machined WAAM. (c) Longitudinal stresses at deposition root in steel plate after loading (140.6 kN) for specimens repaired with WAAM.

was observed at the deposition root owing to the geometrical discontinuity and cooling contraction during the WAAM process, as shown in Fig. 18(a). This causes a new fatigue crack, initiated at the deposition root under fatigue loading, which finally leads to the failure of the plate. The stress level at the deposition root was reduced from 522 to 390 MPa by machining the WAAM details into a pyramid shape, as shown in Fig. 18(c), which was approximately 25% lower than that of the as-deposited WAAM. After 6 million cycles and 3 million cycles with an increased load level, no sign of crack initiation was observed, indicating that the machined WAAM-repair not only arrested the existing crack but also prevented new crack initiation.

3.4. Discussion

3.4.1. Comparison with other repairing/strengthening methods

The WAAM repair method uses two common mechanisms to combat fatigue crack propagation, as described in Section 1. The first introduces an extra stress transfer path, as demonstrated by the static test results (Section 3.1), whereas the second pertains to prestressing by exploiting the residual stresses in the WAAM part built up during cooling and solidification (Section 3.3). In this regard, WAAM repair is very similar to other existing repair/strengthening methods such as weld repair [13,14], CFRP strengthening [4,6], and Fe-SMA strengthening [7,28]. All these methods add extra material on top of the existing steel

elements, with which the stress transferred through the fatigue sensitive position is reduced. More importantly, prestressing was introduced using these methods. Each method has its own mechanism: (1) prestressed CFRP applies prestress by unloading the pre-tensioned CFRP; (2) prestressed Fe-SMA applies prestress by heating the prestrained Fe-SMA followed by a cooling process, with the mechanism being a martensite-to-austenite phase transformation [8], and (3) WAAM repair applies prestress via shrinkage of the deposited WAAM during the cooling process; therefore, it uses the induced residual stresses in a favorable manner to increase the structural performance of the part.

The interface between the substrate (the plate) and repair is a key difference from existing techniques. In this study, the importance of a smooth transition was demonstrated. However, other methods cannot benefit from this smooth transition coupled with the strong interface offered by welding. Load transfer from the CFRP [3] or Fe-SMA [59] is realized through clamping systems that introduce geometric discontinuities and associated stress concentrations. Alternatively, the strips can be adhesively bonded [4,7], which provides smoother load transfer and reduces stress concentrations. However, the adhesive bond may debond from the substrate prematurely [60,61].

WAAM repair combined with machining, a process similar to hybrid manufacturing, avoids the limitations of similar methods as the bonding between the repair and the substrate is based on welding, and the stress concentrations can be mitigated by machining the WAAM profile.

Furthermore, WAAM repair only requires a minor space (30 mm × 30 mm in our case), whereas CFRP or Fe-SMA strengthening requires significantly more space, which could limit their application to cracks on a concave surface. In contrast, WAAM repair can be applied to curved surfaces with minimal effort as the 3D-printed details can be shaped in any way, which highlights the potential of WAAM as a structural repair method. The process can be further enhanced; for example, preheating the surface or optimizing the printing parameters could improve the WAAM-substrate interface and result in a more favorable interface geometry. It would also contribute to further reducing stress concentration at the root. Conversely, the compressive stress applied to the crack may potentially decrease. Single-sided deposition should also be investigated because both sides of the substrate may not be accessible in practice.

Although conventional welding repairs and the proposed WAAM repair have some similarities, they are different in certain ways. The main difference between the two approaches is that WAAM repair can manufacture an optimized topology on top of an existing crack in a way that it minimizes the stress concentrations and the risk of crack initiation in the weld transition. As it has been also discussed in this study, it is possible to engineer the residual stresses in the steel substrate in a favorable way in the WAAM repair. Therefore, as summary, WAAM repair provides the opportunity to optimize the topology of the deposited profile to achieve the required stiffness and residual stress pattern and as the same time minimize the stress concentrations. The situation is different in the conventional welding repair, the welded profile is given and there is not much possibility to optimize the repair solution.

3.4.2. Temperature influence

An influencing parameter was left out of the current study but needs to be shortly discussed; that is temperature. Since the prestressing mechanism exploits thermal stresses, it may be that preheating the plate before the deposition process reduces the prestress as it reduces the temperature difference between the bead and the plate. Investigating the influence of preheating on WAAM repair is an open topic which deserves some future studies.

4. Conclusion

The following conclusions can be drawn from this study:

1. WAAM repair offers two benefits for fatigue strengthening. The first is to reduce the stress level at the crack section via an enhanced cross-sectional area. The second is generating compressive stress at the crack tip during cooling of the deposited WAAM details.
2. FE simulations revealed that the root of the as-deposited WAAM had a large stress concentration, which was the source of new fatigue crack initiation. Microscopic observation of crack initiation further supports this conclusion. The stress concentration can be mitigated by machining the WAAM into a pyramid-like shape.
3. Microscopic analysis reveals that the substrate steel is partially melted and a diffused interface, with a lot of porosity, is formed. Microcracks initiated at the diffused interface were arrested by the micropores.
4. WAAM repair shares similar mechanisms with other repair/strengthening techniques, such as bonded CFRP strengthening, unbonded Fe-SMA strengthening, and welded repair. Major limitations of other strategies, such as stress concentration and premature debonding, can be prevented by WAAM repair.

CRediT authorship contribution statement

E. Ghafoori: Funding acquisition, Conceptualization, Supervision, Writing – review & editing, Project administration. **H. Dahaghin:** Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **C. Diao:** Investigation, Writing – original draft. **N. Pichler:** Formal analysis, Investigation, Writing – original draft,

Visualization. **L. Li:** Formal analysis, Investigation, Writing – original draft, Visualization. **M. Mohri:** Investigation, Writing – original draft, Visualization. **J. Ding:** Resources. **S. Ganguly:** Resources. **S. Williams:** Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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