

EFFECT OF MATERIAL PROPERTIES ON CRACK LENGTH IN DMWJS OF SAFE-END IN PRESSURIZED WATER REACTORS

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Abstract

Dissimilar metal welded joints (DMWJs) are widely used in the primary systems of pressurized water reactors (PWRs), particularly in the connection between the reactor pressure vessel (RPV) nozzle and the safe-end. Due to the differences in mechanical properties between the joined materials and the presence of welding residual stresses, these regions are susceptible to complex crack initiation and propagation behaviour. The present study investigates crack propagation in a DMWJ of an RPV safe-end using the Extended Finite Element Method (XFEM) implemented in ABAQUS. A one-inch compact tension (1T-CT) specimen was developed to represent the dissimilar material region consisting of A508 low-alloy steel, Alloy 182 weld metal, and SS316L stainless steel. Four initial crack configurations were considered near the interfaces between the dissimilar materials. The study mainly examines the effects of residual stress and Young's modulus on the crack propagation path. The numerical results show that residual stress has a significant influence on the direction of crack growth. In the absence of residual stress, the crack generally tends to propagate toward the region with lower yield strength. However, with increasing residual stress, the crack propagation direction changes and shows a tendency to deflect toward the material having higher yield strength. The influence of Young's modulus on crack deflection was found to be comparatively small when compared with the effect of residual stress. The results also indicate that the initial crack location and its distance from the material interface influence the resulting crack propagation behaviour. The findings provide useful insight into the fracture behaviour of DMWJs and may contribute to improved structural integrity assessment of safe-end components in nuclear power plants.

1. INTRODUCTION

Nuclear power plants play an important role in meeting the increasing global demand for electricity. They provide a stable and continuous supply of power while producing very low greenhouse gas emissions during operation. Because of their high efficiency and reliability, many countries continue to depend on nuclear energy as a major part of their electricity generation. However, the safety of nuclear power plants depends largely on the structural integrity of their critical components. These components operate under high temperature, high pressure, neutron irradiation, and cyclic loading for several decades. Therefore, even a small defect can gradually grow into a serious structural problem if it is not detected in time [1].

Among the important structural components of a Pressurized Water Reactor (PWR), the reactor pressure vessel (RPV) and its connected primary piping system receive significant attention because they form the primary pressure boundary of the reactor. The connection between the reactor pressure vessel nozzle and the stainless steel piping is generally made through a safe-end section using a dissimilar metal welded joint (DMWJ). These welded joints combine different materials such as low-alloy steel, nickel-based weld metal, and stainless steel to achieve the required mechanical strength and corrosion resistance. Although this combination improves the overall performance of the system, it also creates material mismatch at the weld interface due to differences in elastic modulus, yield strength, thermal expansion coefficient, and fracture toughness [2].

During fabrication, the welding process introduces residual stresses within the welded joint because of uneven heating and cooling. These residual stresses remain locked inside the material even after the welding operation is completed. During plant operation, they combine with internal pressure, thermal loading, and environmental effects, producing complex stress distributions near the weld interface. As a result, the safe-end region becomes one of the most critical locations for crack initiation and crack propagation. Previous investigations have shown that many degradation mechanisms, including stress corrosion cracking (SCC), thermal fatigue, and primary water stress corrosion cracking (PWSCC), are frequently associated with dissimilar metal welded joints in nuclear power plants [3].

Crack propagation in dissimilar metal welded joints has been studied using both experimental and numerical approaches. Experimental investigations provide valuable information regarding fracture behaviour, but they usually require specialized testing equipment, long testing times, and high manufacturing costs. Moreover, testing nuclear-grade materials under actual operating conditions is often difficult due to safety and economic limitations. Because of these challenges, finite element analysis (FEA) has become an effective alternative for studying crack behaviour in engineering components. Numerical simulations allow different loading conditions, material combinations, and crack configurations to be investigated without performing expensive full-scale experiments.

Several numerical techniques have been developed to simulate crack growth, including the Virtual Crack Closure Technique (VCCT), Cohesive Zone Modelling (CZM), and the Extended Finite Element Method (XFEM). Among these methods, XFEM has gained considerable attention because it allows cracks to initiate and propagate without continuous remeshing of the finite element model. This significantly reduces modelling effort while maintaining good prediction accuracy for complex crack paths. Due to these advantages, XFEM has been widely applied to fracture mechanics problems involving welded joints, composite materials, and structural components subjected to mixed loading conditions [4].

Although many researchers have investigated crack propagation in dissimilar metal welded joints, most published studies have mainly focused on the influence of residual stress or environmental degradation. Comparatively fewer studies have examined how the combined effect of residual stress and material mismatch influences crack propagation in the reactor pressure vessel safe-end region using XFEM. In addition, understanding the influence of different material properties on crack deflection remains important for improving structural integrity assessment and maintenance planning of nuclear power plants.

The present study investigates crack propagation behaviour in reactor pressure vessel safe-end dissimilar metal welded joints using the Extended Finite Element Method implemented in ABAQUS. A one-inch compact tension (1T-CT) specimen based on ASTM E399 was used for numerical analysis. The effects of residual stress and Young's modulus on crack propagation were examined by considering different crack locations near the material interface. The obtained results provide a better understanding of crack growth behaviour in dissimilar metal welded joints and may assist in improving the structural integrity assessment of nuclear power plant components.

2. Material and Methods

2.1. Material

The material behavior was defined using both elastic and plastic material properties in ABAQUS. Since the specimen consists of three different materials, namely A508 low-alloy steel, Alloy 182 weld metal, and SS316L stainless steel, the mechanical properties of each material were assigned separately. These materials are commonly used in reactor pressure vessel (RPV) safe-end dissimilar metal welded joints because they provide a combination of high strength, fracture resistance, and corrosion resistance under the operating conditions of pressurized water reactors (PWRs) [5].

Table 1: Parameters of materials in a DMWJs[6-8]

Materials	Young's Modulus E (GPa)	Poisson's Ratio ν	Yield Stress σ_y (MP)	Hardening Exponent n	Ultimate Tensile Strength σ_u (MPa)	Fracture Toughness J_{IC} (kJ/m ²)
A508	183	0.3	385	4.779	560	224.2
Alloy 182	203	0.3	342	4.375	576	166.6
316L	176	0.3	309	4.08	485	170

2.2. Damage model in ABAQUS

To simulate crack initiation and propagation using the Extended Finite Element Method (XFEM), a suitable damage model is required. The damage model consists of two main parts: the damage initiation criterion and the damage evolution law. These parameters define the conditions under which a crack starts to form and how it continues to grow after initiation. The damage initiation criterion is expressed in terms of a stress ratio:

$$f = \left\{ \frac{\langle \sigma_{max} \rangle}{\sigma_{max}^0} \right\} \quad (1)$$

In this study, the maximum principal stress criterion was selected as the crack initiation criterion. This criterion is widely used for brittle and quasi-brittle fracture problems where crack formation occurs when the tensile stress at the crack tip exceeds the material strength. The maximum principal stress at the crack tip is considered as the main parameter for defining the initiation of damage. where, σ_{max} represents the maximum principal stress developed at the crack tip and σ_{max}^0 represents the maximum allowable principal stress of the material. The Macaulay brackets $\langle \rangle$ ensure that only tensile stresses contribute to crack initiation, while compressive stresses do not produce crack growth.

According to this criterion, crack initiation occurs when the value of the stress ratio f reaches unity:

$$f = 1 \quad (2)$$

At this point, the stress state near the crack tip reaches the critical condition and damage initiation begins. After crack initiation, the crack growth behaviour is controlled by the damage evolution law.

The crack propagation in XFEM is governed by the fracture energy approach. The equivalent energy release rate G_{eq} is used as the controlling parameter to describe the crack evolution. Crack propagation starts when the equivalent energy release rate reaches the critical fracture energy of the material:

$$G_{eq} = G_{eq}^c \quad (3)$$

Where G_{eq}^c represents the critical equivalent fracture energy required for crack propagation.

Since cracks may propagate under different loading modes, the fracture resistance of the material is defined separately for Mode I (opening), Mode II (sliding), and Mode III (tearing) deformation. The critical energy release rates corresponding to these fracture modes are represented as:

$$G_I^c; G_{II}^c; G_{III}^c$$

(4)

In the present study, Mode I crack opening is considered the dominant fracture mode because the compact tension specimen is subjected to tensile loading. Therefore, the contribution of Mode II and Mode III crack-ing is comparatively small and can be neglected. The damage model implemented in ABAQUS XFEM uses the maximum principal stress criterion for crack initiation and fracture energy-based evolution for crack prop-agation.

This approach allows the crack to initiate and grow naturally along the predicted path without requiring continuous remeshing, making it suitable for investigating crack propagation behavior in dissimilar metal welded joints.

2.3. Geometric Model

A typical safe-end dissimilar metal welded joint connecting the RPV nozzle and primary piping can be simplified as a cylindrical structure for numerical analysis. The welded joint geometry was simplified into a compact tension (CT) specimen. This approach reduces the complexity of the model while maintaining the important features of the dissimilar material interface.

A one-inch compact tension (1T-CT) specimen was developed according to the ASTM E399 standard. The specimen consists of three different materials: A508 low alloy steel, Alloy 182 weld metal, and SS316L stain-less steel, representing the typical material combination used in PWR safe-end welded joints. The initial crack was introduced near the interface of the dissimilar materials to study the effect of material mismatch and residual stresses on crack propagation.

The geometry of the safe-end joint location and the 1T-CT specimen used in the ABAQUS simulation are shown in Figure 1. The dimensions of the specimen were selected according to the standard and previous studies to ensure comparable fracture behaviour.

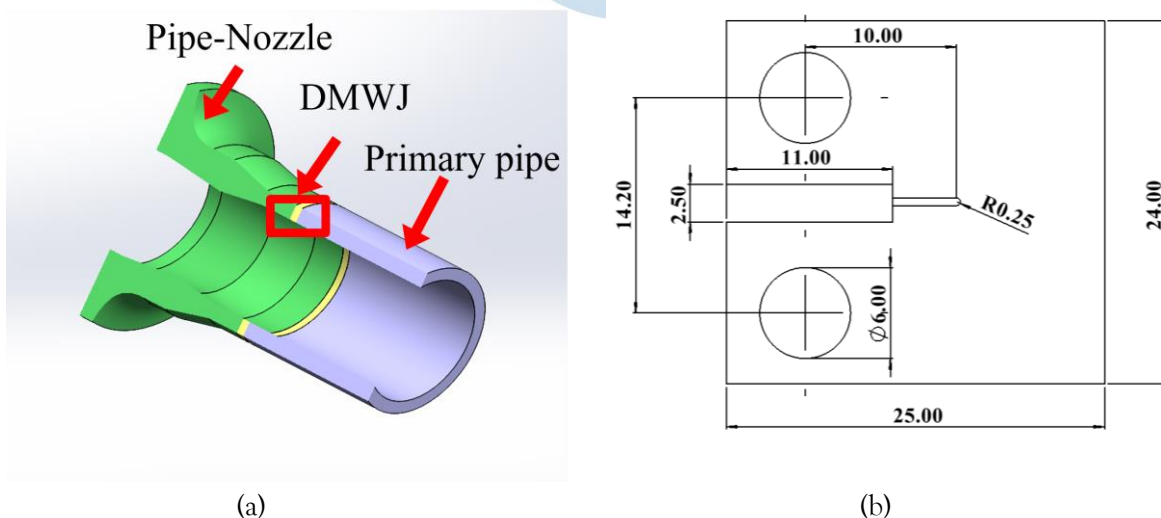


Figure 1. (a)The location of DMWJs (b)Geometry size of 1T-CT specimen

2.4. Elastic-Plastic Behaviour

Materials used in pressurized water reactor DMWJs typically exhibit different mechanical properties because they are selected for different structural and operating requirements. The difference in their mechanical behaviour can affect the stress distribution and crack propagation near the material interfaces.

The elastic-plastic response of these materials was represented using the Ramberg-Osgood relation. This model was used to describe the nonlinear stress-strain behaviour after the material exceeds its elastic limit. The total strain is expressed as the sum of elastic and plastic components:

$$\epsilon = \frac{\sigma}{E} + \alpha \left(\frac{\sigma}{\sigma_y} \right)^n \quad (4)$$

Where E is Young's modulus, σ_y is the yield strength, σ is the applied stress, and n represents the strain-hardening behaviour of the material.

2.5. Mesh Model

A suitable mesh was generated for the numerical model to obtain accurate results during crack propagation analysis. Since high stress and strain gradients develop near the crack tip, mesh refinement was applied in this region. The mesh was gradually coarsened away from the crack region to maintain computational efficiency.

Structured mesh control was assigned to the model to obtain a regular and uniform arrangement of elements. Four-node bilinear quadrilateral plane strain elements, CPE4, were used in the analysis. These elements were selected because the CT specimen was analyzed under plane strain conditions.

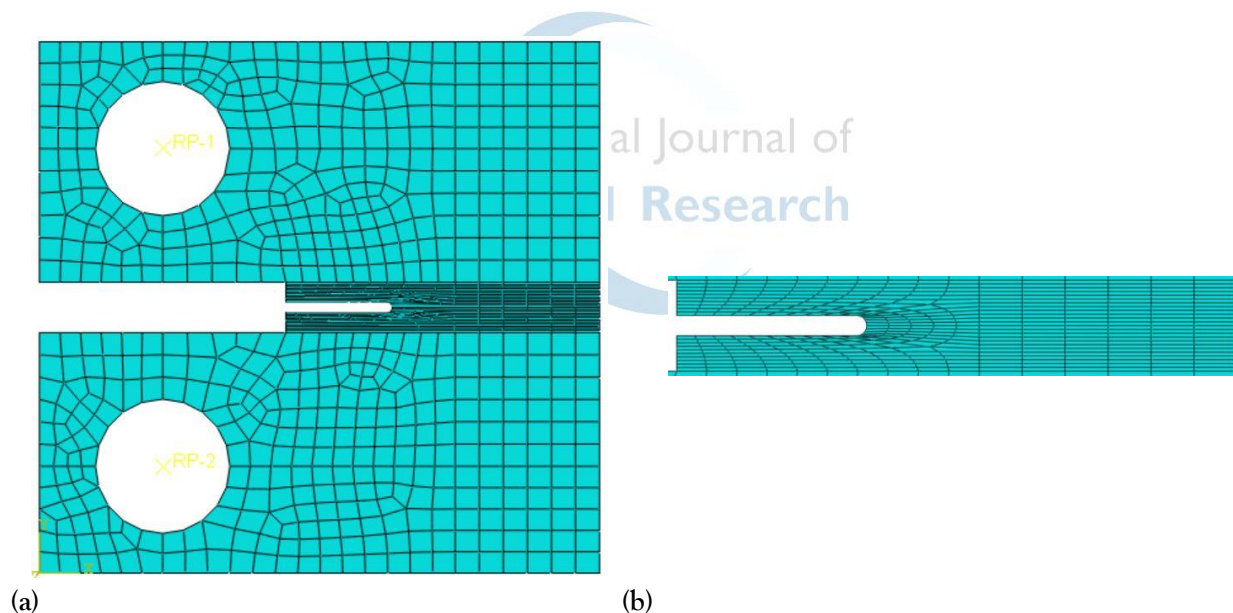


Figure 2. Mesh model: (a) Global mesh (b) the mesh at the crack front

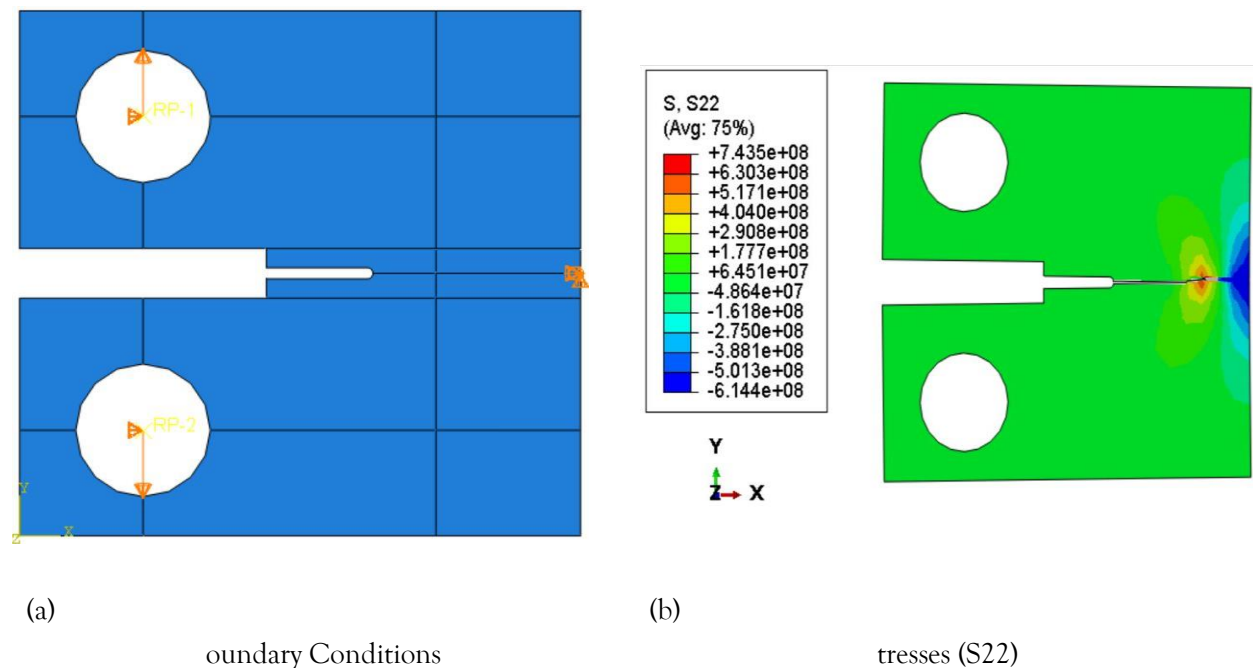


Figure 3. Boundary conditions and crack movement

2.6. Crack Locations Relative to Material Interfaces

Four specimens are used to illustrate the sampling locations near the interface of two materials. Green represents A508, yellow represents Alloy 182, and blue represents 316L. Crack 1 is situated in A508 near the interface of A508 and Alloy 182, crack 2 is located in Alloy 182 near the interface of Alloy 182 and A508, crack 3 is positioned in Alloy 182 near the interface of Alloy 182 and 316L, and crack 4 is found in 316L near the interface of Alloy 182 and 316L.

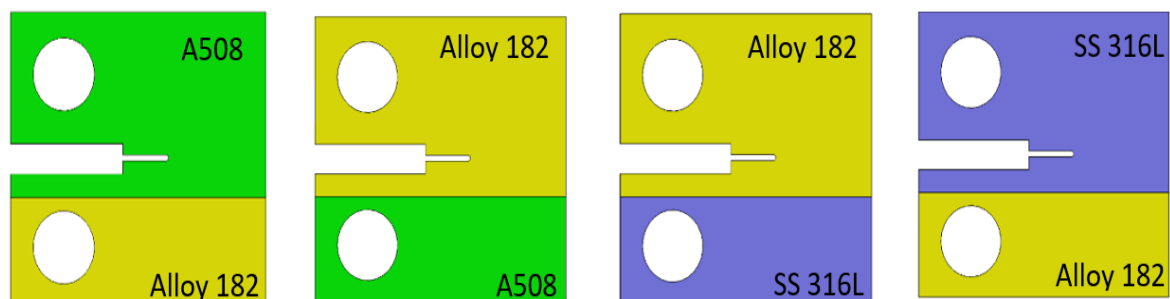


Figure 4. Location of four cracks

3. Results and Discussions

For the first specimen, the crack initially propagated towards the interface between the two materials when the effect of residual stress was neglected. This behaviour is mainly controlled by the difference in material properties across the weld interface. However, after introducing the residual stress field, the crack propagation direction changed noticeably. The tensile residual stresses developed in the A508 region increased the crack driving force, causing the crack to extend further into the base material instead of continuously moving towards the interface. As the residual stress level increased, the crack path became more stable and followed a nearly straight trajectory through the A508 steel.

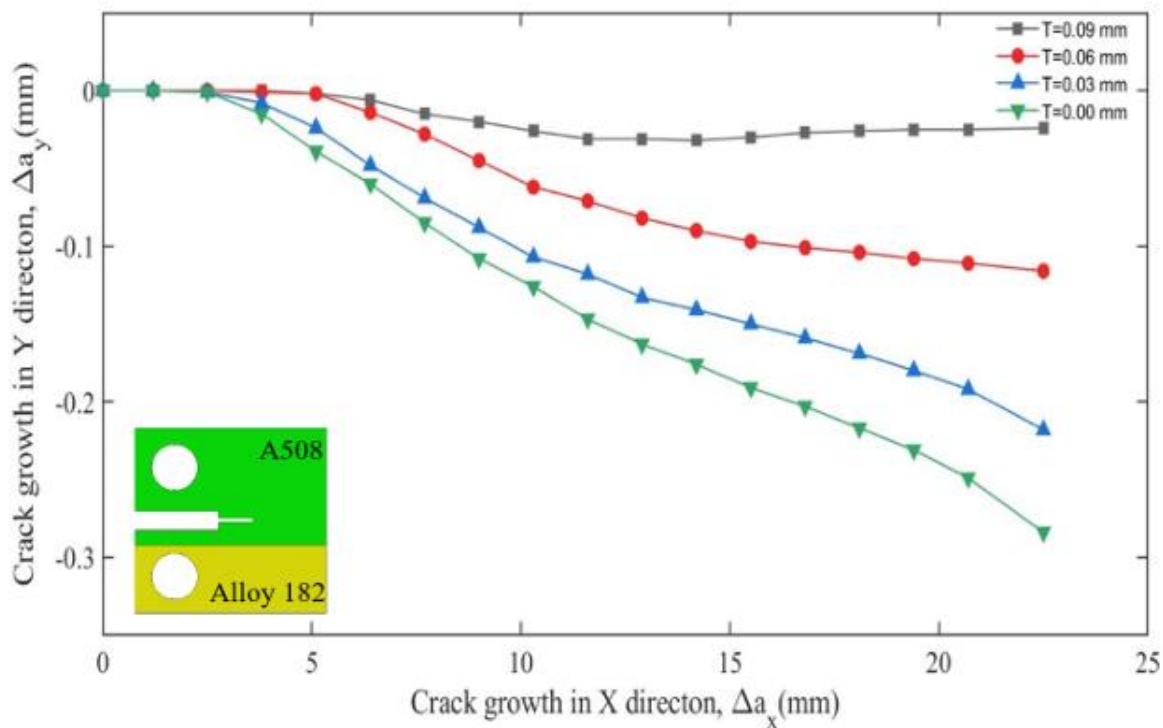


Figure 5. Propagation path of crack 1 under different residual stress

Young's modulus is one of the fundamental mechanical properties that describes the stiffness of a material. A material with a higher Young's modulus undergoes less elastic deformation under the same applied load, while a material with a lower Young's modulus experiences greater deformation. Since dissimilar metal welded joints consist of materials having different elastic properties, it is important to investigate whether the difference in Young's modulus influences the crack propagation behaviour. To evaluate this effect, two different cases were considered in the present study. In the first case, each material was assigned its actual Young's modulus obtained from the literature. In the second case, the Young's modulus of both materials was assumed to be the same while keeping the remaining material properties unchanged. The crack propagation paths obtained from these two cases were then compared. For Specimen 1, only a small difference in the crack propagation path was observed between the two cases. The crack continued to propagate in nearly the

same direction whether the Young's modulus was identical or different. This indicates that the stiffness mismatch between the two materials has only a limited influence on the crack growth behaviour when the crack is located inside the higher-strength material.

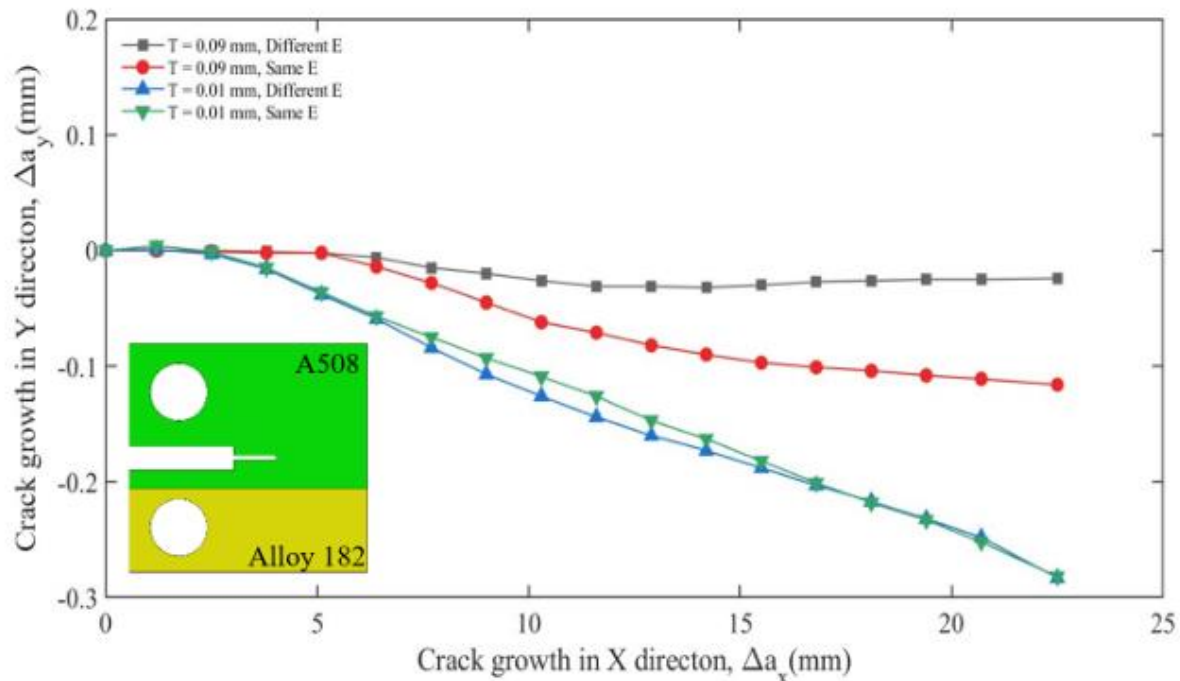


Figure 6. Propagation path of crack 1 under different Young's Modulus.

4. Conclusions

The numerical results showed that material properties have a noticeable influence on crack propagation behaviour. The mismatch between the mechanical properties of the base metal, weld metal, and stainless steel changes the stress distribution around the crack tip, which affects both the crack driving force and the crack propagation direction. As the crack approaches the material interface, the redistribution of stresses becomes more complex because each material responds differently to the applied load. This behaviour demonstrates that the fracture response of a dissimilar metal welded joint cannot be represented accurately by assuming uniform material properties throughout the specimen. The influence of Young's modulus was also investigated by comparing crack propagation under identical and different elastic moduli. The comparison indicated that changing the elastic stiffness alone produced only minor changes in the crack trajectory. Although small variations in the stress field were observed near the crack tip, the overall crack propagation path remained nearly unchanged. This suggests that within the range of elastic properties considered in this study, Young's modulus has a relatively small effect on crack deflection compared with other mechanical properties.

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