Fracture analysis of cladded components considering residual stresses

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The present study is concerned with an experimental and numerical investigation of the behavior of sub-clad and surface cracks in cladded components considering the residual stress field due to the welding and heat treatment processes. For this purpose, two large-scale tests on cladded cracked specimens have been performed and analyzed numerically. It is observed that the fracture process is initiated in the heat affected zone of the base metal underneath the cladding whereas the cladding remains intact even in case of a brittle crack extension and arrest in the base material.

1 Introduction

In many fields of power generation and chemical plant technology, pressure vessels and pipes consisting of ferritic steels are supplied with an austenitic welded cladding on their interior surface. Within this principle of construction, the ferritic base material carries the load, whereas the austenitic cladding protects the load carrying parts of the structure from corrosion. Cladded components are usually assessed by fracture mechanics methods since the weldment might contain micro defects nucleated by welding process, which are not easily detectable by non-destructive test methods. The fracture assessment of cladded components is difficult due to the complex residual stress field caused by the manufacturing process. Objective of the present study is an investigation of the effect of the residual stress field on the fracture behavior of cladded components and possible beneficial effects of the ductile cladding by bridging of cracks assumed within the more brittle base metal.

2 Experimental investigation

In the experimental investigation, two large scale plates ($700 \times 220 \times 74\,\mathrm{mm}$) consisting of a ferritic 22NiMoCr3-7 pressure vessel steel were cladded with an austenitic material. One of the plates was supplied with a semi-elliptical fatigue crack prior to cladding in order to form a sub-clad crack. The second plate was supplied with a notch of similar dimensions in the base metal which was cut through the cladding after the welding process. As in an earlier study (Hodulak et al. [1]), both specimens were tested under three-point bending with a superimposed (stationary) thermal gradient until final fracture (Fig. 1).

In the test of the specimen with the through-clad crack, an initiation followed by a crack arrest was observed at an interim load level. During this crack propagation in the base metal, the cladding remained intact except some local effects. The fractographic investigation revealed that the base metal failed by pure transgranular cleavage. The initiation spot was detected in a coarse grain area directly underneath the cladding (see Fig. 2). For the specimen with the sub-clad crack, no interim initiation and arrest prior to final fracture close to the limit load was observed. Again, the cladding remained stable until the final failure. The cleavage failure in the base metal was triggering by a large sulphide inclusion located approximately 2 mm underneath the cladding. Full details on the experimental procedure and results are given in the final report (Hohe et al. [2]).

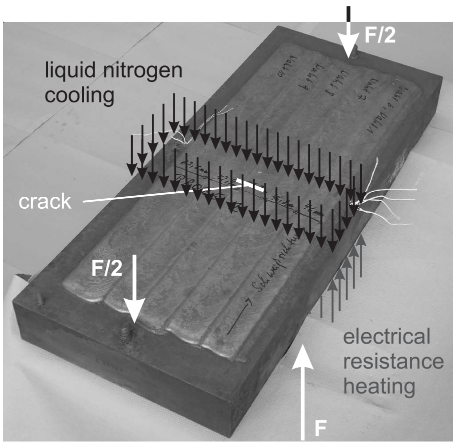

Fig. 1 Large-scale specimen.

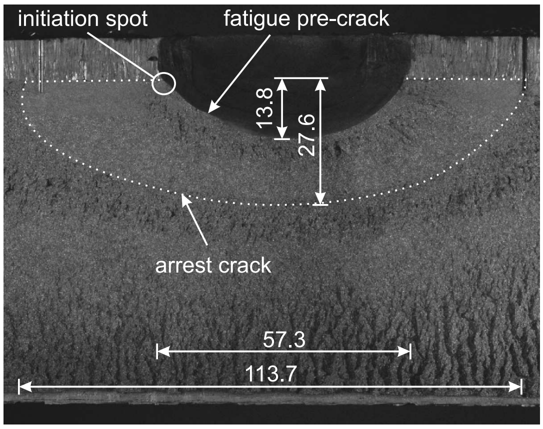

Fig. 2 Fractographic investigation.

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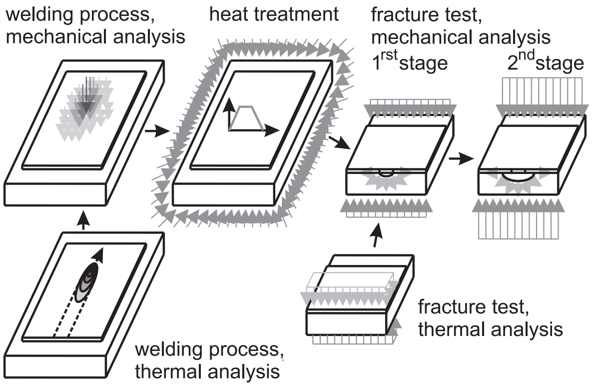

Fig. 3 Simulation sequence.

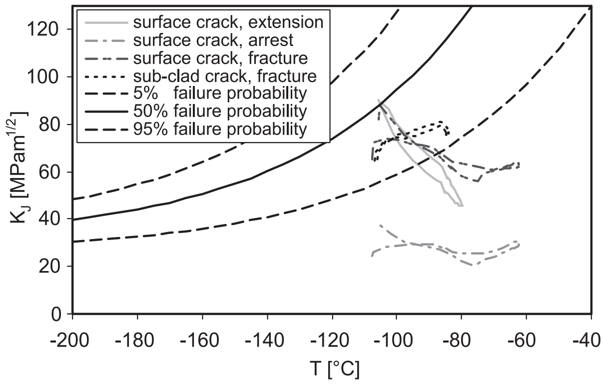

Fig. 4 Fracture mechanics assessment.

3 Numerical simulation

For a further assessment, the large scale tests were simulated numerically using the finite element method. In this context, the entire process chain of the welding and subsequent heat treatment processes for preparation of the specimens were simulated in order to obtain a detailed result for the residual stress field. Due to the different requirements of mesh resolution, symmetry of the loading conditions etc., all steps of specimen preparation and tests were simulated separately with a transfer of the results from the previous step as initial conditions (Fig. 3). The residual stress field after the welding process has a periodic character with distinct peaks in the tensile and compressive stresses (Siegele and Brand [3]). The distinct peaks are declined due to creep deformation during the heat treatment. Nevertheless, the periodic character of the residual stress field with tensile stresses in the cladding and compressive ranges in the base metal underneath the cladding remains.

The fracture mechanics assessment of the ferritic material range was performed in terms of the local stress intensity factor $K_{\mathrm{J}} = \sqrt{EJ/(1-\nu^2)}$ along the crack front, computed from the local J-Integral. In Fig. 4, the stress intensity factors at the instants of interim crack initiation, arrest and final failure of the specimen with surface crack as well as at fracture of the specimen with sub-clad crack are presented as a function of the local temperature along the crack front. For both initiation events of the specimen with surface crack, quite similar maximum stress intensity factors are obtained, which are close to the fracture toughness curve for 50% cleavage probability as obtained on fracture tests using standard small-scale specimens of the material under consideration. Along the crack front of the sub-clad crack, lower local failure probabilities are computed for the instant of final fracture. Nevertheless, non-negligible cleavage probabilities along the entire crack front indicate a large amount of stressed volume resulting in a higher overall probability of failure. In all cases, the location of the maximum failure probability coincides with the cleavage initiation spot determined in the fractographic investigation.

The fracture assessment of the austenitic cladding was performed by a comparison of the local J-Integral with the respective crack resistance curves. Except some strictly local effects due to model simplifications, no critical values were obtained throughout the deformation history of both large-scale tests, revealing that the failure of the cladding was a secondary fracture event following the brittle failure of the base metal.

4 Conclusions

The present study is concerned with the fracture assessment of cladded ferritic components. In two large-scale tests and a subsequent numerical simulation, it is demonstrated that the brittle failure of the cladding is in general the more critical event compared to a possible ductile crack extension within the cladding. The complex residual stress field caused by the welding and heat treatment processes is found to have distinct effects on the fracture behaviour.

Acknowledgement

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References

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