THE FRACTURE RESISTANCE OF BIMATERIAL COPPER-STAINLESS STEEL INTERFACES WITH THREE-POINT BEND CONFIGURATION

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Interfaces between different materials are responsible for strength mismatch, which introduces several new mechanisms of material failure as well as complicates the understanding of fracture behavior. This study concentrates on characterizing the properties of AISI 316 LN and CuCrZr explosion welded (EXW) joints under delivery and post-weld heat treated (PWHT) conditions. Fracture mechanical testing and numerical analysis were combined in order to characterize the interface properties and factors responsible for the observed behavior. Results demonstrated the usability of EXW-joining in producing interfaces with adequate structural strength and presented the transition in type of fracture at room and higher temperatures. The fracture resistance is found to be significantly enhanced due to PWHT, while the testing temperature affects the crack propagation behavior between the interface and the softer material.

INTRODUCTION

Several modern applications demand incorporation of complex material combinations or different types of functional materials. Especially applications designed for fusion use have been one of the pacesetters when determining the usability and structural behavior of advanced bimaterial joints. This study focuses on AISI 316LN and CuCrZr EXW joints, which are planned to operate in a cooling system subjecting them to severe thermal loading.

Joints between AISI 316 LN and CuCrZr experience complex behavior due to several factors. At first, the manufacturing process exposes the materials to high local deformations, causing plastic straining and transformations in microstructural properties. The effects of PWHT are to be considered in this instance as well. As a second factor the other base metal, CuCrZr, possesses in continuum terms complex properties including viscoplastic and creep behavior under conditions, which can be attained in use and in the EXW process. The behavior of the joint interface, referring to the effects of possible initial porosity and damage are another factor to consider, adding up to a structural system experiencing several different possible fracture mechanisms and affecting parameters.

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This work presents experimental results of fracture mechanical testing of the EXW joints under as received EXW and PWHT conditions. The microstructural features are described in addition to results from numerical modeling, which are used in interpreting the results of this work.

NUMERICAL MODELING

When introducing an interface to a near crack tip location, most of the basic solutions of fracture mechanics lose their validity due to limitations of homogeneous material distribution. Some of the models, mainly the HRR-field, can be modified by accommodating the mismatch as an additional parameter in describing the stress distributions, but in general terms the nature of stress fields and their amplitude parameters remains under debate or unknown. Due to these complexities and because of the nonlinearities causing additional difficulties in mismatch behavior, the single edge notched bend configuration was modeled with FEM by using constitutive models, which were incorporated to feature the material properties measured from near interface locations by tensile test specimens.

J-integral Determination. The mismatch chosen for a particular set of calculations was determined not by using the M-factor as traditionally, but by using a more suitable definition related to the entire constitutive behavior:

$$M_* = \frac{\int_0^{\varepsilon_e^1} \sigma_e^1 d\varepsilon^1}{\int_0^{\varepsilon_e^2} \sigma_e^2 d\varepsilon^2}, \qquad (1)$$

where σ_e^i and ε^i denote the values of equivalent stress and strain for material i, and ε_e^i is related to a certain cut-off strain. In this study, ε_e^i was chosen such that further straining would not cause deviation to the mismatch factor determined from equation (1). In the linear-elastic regime, M_* is nearly equal to the M factor, but because we are interested in differences of the entire constitutive equation, which affect structural behavior, we use in general the definition given above. M_* and M can be easily related, and after simplifying for a power-law hardening material to achieve uniqueness:

$$M_* = M + M\frac{\Delta\varepsilon}{\varepsilon_{ys}^2} + \frac{\dfrac{E^1(a_1)^{n_1+1}}{(n_1+1)(\varepsilon_{ys}^1)^{n_1}}}{\dfrac{E^2(a_2)^{n_2+1}}{(n_2+1)(\varepsilon_{ys}^2)^{n_2}}}, \qquad (2)$$

where $\Delta\varepsilon$ is the difference in reference strains $\left(\varepsilon_{ys}^{i}\right)$, n_i are the strain hardening exponents, E^i the Young's modulus and $a_1 = a_2 = 100$ for attaining the necessary uniqueness for all combinations of the constitutive parameters. The η-factors for J-integral were determined and are presented in Figure 1 for different values of M_*. Notice the nonlinearity, which means that direct comparisons without filtering the data are limited.

Equivalent Plastic Strain and Hydrostatic Stress. In Figure 2 the equivalent plastic strain is presented on both material sides, and for comparative purposes equal result for a homogeneous specimen is provided. The concentration of strain on the side of the softer material is observed, which in this instance is the CuCrZr alloy. The strain distribution has some characteristics resembling results from mixed-mode crack tip analyses. Contour plots about the crack tip region demonstrate that the localization of deformation and the peak value of strain are found close to the interface from the side of the CuCrZr alloy. Considering the distributions of hydrostatic stress as presented in Figure 3, the peak maximum when considering rays emanating from the notch face present that the maximum values are found from the interface and, on the other hand, from the softer material very close to the interface.

In continuum sense, the nucleation of fracture should occur from the side of the softer material most likely very close to the interface, at least when the fracture process is controlled by the plastic strains and the basic strength of the joint is strong enough to withstand continuum treatment. The propagation process in this case will follow the maximum of plastic strain but will not deviate too far from the interface, because this will cause a decrease in plastic strain and hydrostatic tension due to the loss of stress intensification effect. In order to attain pure interface fracture, the fracture process must be controlled by the maximum of hydrostatic or tensile stresses, or in a more practical sense deficiencies in bonding cause the process to localize to the interface.

EXPERIMENTAL

Microstructural Features and Mechanical Properties. In the EXW process the material near the interface experiences severe plastic deformation resulting in a residual state of plasticity. The introduction of dense dislocation networks and structures results in the loss of strain hardening capacity along with the formation of a zone of less ductile material. In a matter of fact, the CuCrZr near the joint, which naturally deforms much more than the harder AISI 316 LN, behaves in tensile tests nearly in a linear-elastic manner, demonstrating the loss of ductility associated with the EXW method. In PWHT the copper alloy recrystallizes and the ductility associated with the initial state is restored. CuCrZr alloy experiences rate dependent yield, which is another factor contributing to the complexity of the joint behavior in addition to creep behavior at higher temperatures. More detailed presentation of the microstructural basis is given in Tähtinen et al (1) and (2).

Fracture Resistance Testing. J-R curves are presented in Figure 4 for the EXW and EXW-PWHT joints. The PWHT was able to increase the fracture resistance of the EXW joint approximately threefold. When conducting the tests at room temperature, the crack propagation occurred at the side of the copper alloy, deviating from the interface in a constant angle but still retaining a defined distance reflecting the effect of the interface as a stress concentrator.

Effects of Higher Temperatures. During constant load creep testing different crack propagation behavior when compared to the tensile test behavior was observed. No fracture mechanical testing was conducted yet, but it was observed that higher temperatures can change the situation with respect to material failure. Conducting tests at 300°C it was discovered that the path of crack growth changes from the CuCrZr alloy to the bond interface.

DISCUSSION

Room Temperature Behavior. Tests conducted at room temperature demonstrated, that in all cases and at all states of heat treatment the fracture propagated to the weaker CuCrZr alloy. Experimental observations on crack paths found also the effects of the interface in a way that the crack growth as a function of propagation length would not deviate from the interface consistently among further growth. Numerical analyses as a function of mismatch presented the localization of plastic deformation near the interface in the softer material (maximum approximately fivefold). The degree of mismatch encountered within the tensile properties of EXW and PWHT joints was in all cases enough to cause similar behavior, referring that the presence of an interface in practical situations is already necessary to cause the concentration of deformation. The degree of intensification of plasticity with PWHT joints was in quantitative terms less, i.e. the load carrying and strain distribution of the joint was more uniform, causing the significant increase in fracture toughness as observed from the results of fracture mechanical testing. The other factor contributing to the fracture toughness increase is naturally the PWHT in itself, i.e. microstructural changes. The high dislocation density of the EXW joint works as an initial distribution of damage, which results in extension of the process zone, loss of strain hardening capability and is responsible for the flat, low tearing modulus, appearance of the fracture resistance curves. Since the fracture resistance increase after nucleation is due to plastic dissipation, it can be argued that the homogenization of deformation is mainly responsible for the higher value of nucleation toughness with PWHT joints, while the higher value of tearing modulus is primarily a result of the post-weld heat treatment.

At room temperature the situation can be treated as a fracture process, where the crack tip plasticity plays the most important role, and the crack path is governed by a combination of localization of deformation and stress concentration effect of the interface.

Higher Temperatures. The increase of temperature to 300°C lead to a transition in fracture mechanism found from constant load creep tests. The crack path changes from the fracture of the softer material to interfacial fracture. The considerations given in the previous chapter are valid for higher temperature analyses as well, but the effects of thermal excitation need further consideration. It appears that the creep process is more controlled by the tensile stresses and hydrostatic stress, which enhance interfacial fracture since the highest value of hydrostatic stress is found at very close proximity to the joint and is directly related to the misfit of elastic constants. With high values of mismatch, excited by thermal degradation of mechanical properties, the values of maximum hydrostatic stress move closer to the interface and closer to the notch tip. Both factors enhance the effective loading of the interface. The main factors responsible for the crack path transition appear thus to be the tensile stress controlled nature of the creep process when combined to presence of the interface as a stress concentrator and as a source of initial damage. Also, high values of mismatch promote interfacial failure further, because under higher temperatures the stronger localization of plasticity lowers the driving force on the softer material due to lowering stress state (mode I prominent), again increasing to the interface induced elastic stress state. The residual stress and strain states following EXW, which experience a high gradient near the joint are also contributing factors. Additional effects, which can not be evaluated on the basis of present work, are the effects related to viscoplasticity and creep (quantitatively) not forgetting their interactions.

CONCLUSIONS

Properties of EXW and PWHT AISI 316 LN and CuCrZr joints were examined at different temperatures through fracture mechanical and supporting testing. Numerical analyses were conducted to determine the prime factors contributing to the observed behavior. The results of the study can be summarized as follows:

- The effect of PWHT on EXW joints is a significant increase of toughness resulting in adequate fracture toughness of the joint, as demonstrated by fracture mechanical testing and numerical simulations.
- Numerical analyses demonstrated the localization of deformation to the side of the softer material, i.e. CuCrZr alloy.
- Maximum values of tensile stress were found near the interface, favoring interfacial fracture under higher mismatch and creep conditions.
- Crack propagation at room temperature was governed by the properties of the weaker material and the mismatch effect of the interface.

ACKNOWLEDGEMENTS

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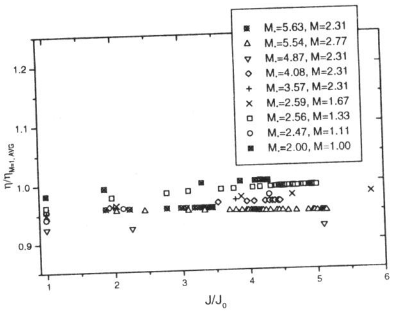

Figure 1 Effect of mismatch on normalized J-solution. The origins of mismatch affect the end solution, i.e. the J-solution is not directly proportional to mismatch in nonlinear terms.

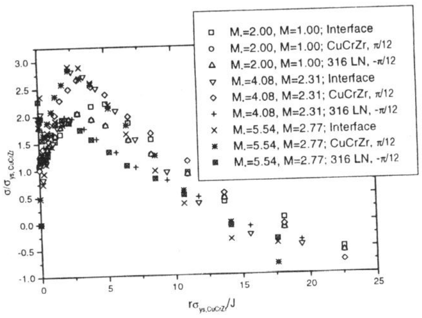

Figure 3 Effect of mismatch on the distribution of hydrostatic stress at and near the interface.

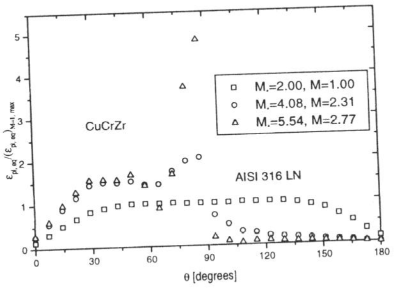

Figure 2 Distribution of normalized equivalent plastic strain at the notch tip with different values of mismatch.

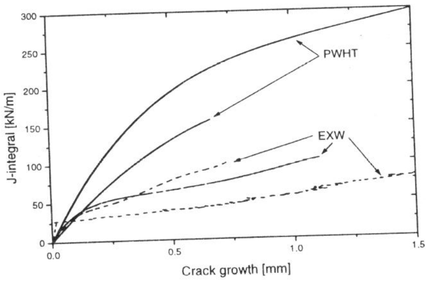

Figure 4 Fracture resistance curves for joints in delivery conditions and after PWHT.