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Effect of Martensitic Transformation of Low Cycle Fatigue in Metastable Austenitic Stainless Steel

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To achieve carbon neutrality by 2050, 50,000 m^3 liquefied hydrogen storage tanks are being developed. A key design challenge is fatigue from repeated refilling and seismic events. The fatigue crack propagation behavior at cryogenic temperatures, especially with the martensitic transformation of austenitic stainless steels, is unclear. In this study, low-cycle fatigue tests were performed at different temperatures and materials to investigate the relationship between crack tip opening displacement (CTOD) and crack growth rate. The effect of martensitic transformation on CTOD was quantified by electron backscatter diffraction. These results were used to estimate crack propagation in large tanks.

NOMENCLATURE

a	Crack length
a_0	Initial crack length
B	Specimen thickness
$\bar{c}$	Converted crack dimension
CTOD	Crack tip opening displacement
$\mathrm{d}a/\mathrm{d}N$	Fatigue crack propagation rate
E	Young's modulus
F	Correction function
K	Stress intensity factor
K_ε	Coefficient of strain concentration
m	Constraint factor
P	Load
r_p	Plastic rotation factor
R_Y	Yield ratio
V_g	Clip mouth opening displacement
W	Specimen width
Y	Correction factor for stress intensity factor
z	Knife-edge height
$\Delta\varepsilon_p$	Plastic strain range
ε	Strain
ε_Y	Yield strain
ν	Poisson's ratio
λ	Compliance
$\bar{\sigma}$	Mean stress
σ_b	Bending stress
σ_y	Yield stress

INTRODUCTION

Background

Climate change, most notably in the form of global warming, is driven by greenhouse gas emissions, with the reduction of carbon dioxide being a key global issue. As a result, the concept of "carbon neutrality," which aims to reduce net carbon dioxide emissions from human activities to zero, has been gaining widespread attention. Achieving this goal requires expanding the use of renewable energy. As part of this effort, liquefied hydrogen is being considered as an energy carrier, and plans are underway to develop the necessary hydrogen infrastructure (Kimura et al., 2022).

For the stable storage of liquefied hydrogen, large storage tanks—about ten times the size of existing ones—are essential. However, the temperature of liquefied hydrogen is 20K, an extremely low temperature that most existing structures have not encountered. The accidental failure of these tanks could have severe consequences.

SUS316L, a metastable austenitic stainless steel, is being evaluated as a candidate material for these tanks due to its relatively high toughness at low temperatures and its resistance to hydrogen embrittlement and corrosion. However, it has been argued that the fracture toughness of SUS316L is affected by martensitic transformation, pre-strain, stress field, and hydrogen embrittlement at cryogenic temperatures (Freire et al., 2023, 2024; Morohoshi and Tsuda, 2023; Morohoshi et al., 2024; Uranaka et al., 2024). In particular, the formation of martensite is closely linked to the material's low-cycle fatigue (LCF) properties.

History of Martensitic Transformation Effects on LCF and Aim of this Study

The influence of martensitic transformation on LCF has been previously suggested (Nakajima et al., 2011). In stable austenitic stainless steels, a reduction in the crack propagation rate was observed as yield stress and tensile strength increased, although no significant temperature dependence was noted. Conversely, in metastable austenitic stainless steels, additional factors beyond yield stress and tensile strength were identified, with slower crack propagation being correlated with an increase in work-induced martensite formation (Baudry and Pineau, 1977).

Moreover, work-induced martensitic transformation has been shown to enhance fatigue life across various alloy types (Bathias and Pelloux, 1973). The mechanism by which this transformation influences fatigue behavior is primarily attributed to the introduction of compressive residual stresses in the surrounding material due to the volumetric expansion associated with martensitic transformation, which subsequently reduces the driving force for crack propagation (Khan and Ahmed, 1996). However, the formation of martensitic phases also alters the overall stress field (Schmitt

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