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Effect of inclusions on fracture behavior of cast and wrought 13% Cr-4% Ni martensitic stainless steels

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ABSTRACT

Microstructures and inclusion characteristics of cast and wrought 13% Cr-4% Ni martensitic stainless steels were related to tensile, fracture toughness J_{Ic}, and Charpy V-notch absorbed energy. A lower volume fraction of inclusions, a larger number of inclusions smaller than 10 μm, and a more resistant inclusion type against rupture and against micro-void formation were the key parameters explaining why the wrought steel has better mechanical properties than the cast steel. It has been shown that TRIP effect occurs only in a small region of 6 mm length from the crack plane in J_{Ic}-test.

1. Introduction

Since the 1960s, different grades of soft martensitic stainless steels such as 13% Cr-1.5% Ni, 13% Cr-4% Ni, 16% Cr-6% Ni and 17% Cr-4% Ni have been produced [1]. Among these grades, 13% Cr-4% Ni steel is used to fabricate hydraulic turbine runners because of its good corrosion resistance, good resistance to cavitation erosion, excellent weldability, and good castability [2–4]. This steel is also used in compressor cones, pump bowls, and petrochemical industries [5].

Delta ferrite is known to have deleterious effects on the mechanical properties of chromium martensitic stainless steels, especially on fracture toughness and absorbed impact energy [5–7]. This can be caused by carbide precipitation at delta ferrite grain boundaries during heat treatment; the precipitates acting as crack initiation and propagation sites [8,9]. As a consequence, nickel was added to the chromium martensitic stainless steels to remove the delta ferrite and improve toughness [1,10]. However, often, some supercooled delta ferrite can be found along prior austenite grains; especially in the case of cast martensitic stainless steels. This is due to the segregation of ferrite-promoting elements during solidification which stabilizes the delta ferrite at room temperature.

In the as-quenched state, the microstructure of 13% Cr-4% Ni martensitic stainless steels is a combination of lath martensite and small amounts of delta ferrite. During subsequent tempering at around 600 °C, the martensite is partially transformed into stable austenite, forming the so-called "reformed austenite" phase. This reformed austenite is thermally stable even if the steel is quenched in liquid nitrogen (−196 °C) [5]. On the other hand, tempering at higher temperatures would lead to the formation of thermally unstable austenite which turns into fresh martensite during cooling [1,8].

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Nomenclature

a_0	inclusion size
E	Young's modulus
e_f	elongation at fracture
e_u	uniform elongation (before necking)
f	volume fraction of inclusions
$H(d)$	harmonic mean value of inclusion diameters
J_{Ic}	J-integral value at the initiation of stable crack growth
J-R curve	J-Resistance curve
K_{Ic}	plane strain stress intensity factor
T	tearing modulus
α	stress concentration factor around an inclusion
γ_{re}	reformed austenite
γ_s	surface energy
Δa	crack extension
λ	inclusion spacing
0.2% σ_y	0.2% offset yield strength
σ_y	yield strength
σ_{UTS}	tensile strength
σ_{void}	required stress for void nucleation

Acronyms

ACI	Alloy Casting Institute
CT	Compact Tension specimen
CVN	Charpy V-Notch
EDX	Energy Dispersive X-ray
FEM	Finite Element Modeling
LEFM	Linear Elastic Fracture Mechanics
MVC	Micro-Void Coalescence
RD	Rolling Direction
SEM	Scanning Electron Microscope
TD	Transverse Direction
UNS	Unified Numbering System
XRD	X-Ray Diffraction

The reformed austenite is mechanically unstable, and transforms into martensite under applied deformation [4,5]. This transformation-induced plasticity (TRIP) is an important mechanism which contributes to the high mechanical properties of 13% Cr-4% Ni martensitic stainless steels. It retards necking during uniaxial loading by increasing the strain hardening of the alloy leading to a significant increase of the material strength. Bilmes et al. [2,5] studies showed that a microstructure without delta ferrite, consisting of tempered martensite and uniformely dispersed reformed austenite results in a good combination of strength and ductility. During crack propagation, the strain energy of the crack tip leads to the transformation of this *metastable* austenite into martensite and part of the energy which is needed to create new surfaces is absorbed by this transformation increasing the material toughness. Furthermore, compressive stresses produced by the volumetric expansion (about 4%) made by the formation of the martensite phase can close and deflect the crack tip [11]. It has been shown by Thibault et al. [4] that TRIP effect also takes place during fatigue crack propagation in cast and wrought 13% Cr-4% Ni martensitic stainless steels.

Density, spacing, and size of inclusions are the principle parameters that affect micro-void formation in dimpled rupture. Lower density and higher spacing of inclusions provide less nucleation sites for micro-void formation, improving fracture toughness [12–14]. Inclusion size plays also an important role in dimpled rupture. Investigations made by Gurland and Plateau [15] showed that as inclusion size increases, the stress needed for void nucleation decreases by the following equation:

$$\sigma_{void} = \frac{1}{\alpha}\left(\frac{E\gamma_s}{a_0}\right)^{0.5} \tag{1}$$

where σ_{void} is required stress for void nucleation, α is stress concentration factor around the inclusion, γ_s is the surface energy needed to create new surfaces and a_0 is the inclusion size. Micro-voids initiate by matrix-inclusion decohesion and/or by inclusion rupture. In most cases, large inclusions fracture at low strains [16]. Further, large inclusions generally

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