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Effect of Silicon Content on the Corrosion Resistance and Radiation- Induced Embrittlement of Materials for Advanced Heavy Liquid Metal Nuclear Systems

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Task 20

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BACKGROUND

Recent studies at the Los Alamos National Laboratory (LANL) involving martensitic Alloy EP-823 containing different silicon content have revealed a beneficial effect of Si on corrosion resistance in a molten lead-bismuth-eutectic (LBE) environment. Since very little data exist in the open literature on the beneficial effect of Si on the corrosion resistance of martensitic alloys, a research task was initiated to explore the role of Si not only on the corrosion resistance but also on high-temperature deformation and radiation-induced embrittlement of modified T91 (9Cr-1Mo-0.24V) grade stainless steels.

This task is primarily focused on the evaluation of the effect of Si content on the susceptibility of modified 9Cr-1Mo-0.24V steel to stress corrosion cracking (SCC) and localized cracking in both molten lead-bismuth eutectic (LBE) and an aqueous solution of acidic pH.

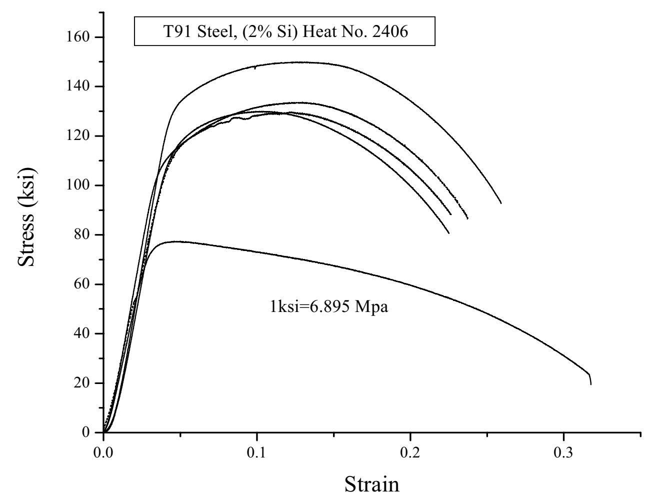
Further, significant efforts are in progress to characterize the deformation mechanism of modified T91 grade steel as a function of temperature and strain rate. Simultaneously, surface analyses of the tested materials are ongoing using state-of-the-art techniques including scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

RESEARCH OBJECTIVES AND METHODS

Four different experimental heats of ASTM A213 Type T91-grade alloy steels (similar to Mod9Cr-1Mo) with different Si content (0.48, 1.02, 1.55 and 1.88 weight percent) have been melted by a vacuum-induction-melting (VIM) practice at the Timken Research Laboratory. An additional four heats containing higher Si content were also melted by the VIM practice, which are also being studied for detailed metallurgical and corrosion characterization. All eight heats were subsequently processed into rectangular and square bars by forging and hot-rolling. These bars were then austenitized, oil-quenched, and tempered to achieve fine-grained and fully-tempered martensitic microstructure.

Tensile testing of T91 grade steels having Si content ranging between 0.48 and 1.88 weight percent were completed, as a function of temperature relevant to the transmutation process. The role of strain rate on the tensile properties is also under investigation. The tensile properties are being interpreted in terms of the yield strength (YS), ultimate tensile strength (UTS), percent elongation (%El), and percent reduction in area (%RA). The morphology of failure at the primary fracture surface is being investigated by SEM as a function of the testing temperature.

In order to better understand the plastic deformation of all four heats, TEM is being employed to characterize the nature of imperfections such as dislocations. Simultaneously, the microstructural variations are being investigated by using both TEM and optical microscopy (OM).



Engineering stress-strain (s-e) diagram vs. temperature.

The susceptibility of the test materials to SCC has been investigated in the presence of molten LBE using self-loaded specimens (C-Ring/U-Bend) at LANL. Simultaneously, SCC testing involving all four heats is in progress at UNLV in the presence of an acidic aqueous solution at temperatures ranging between ambient and 90ºC.

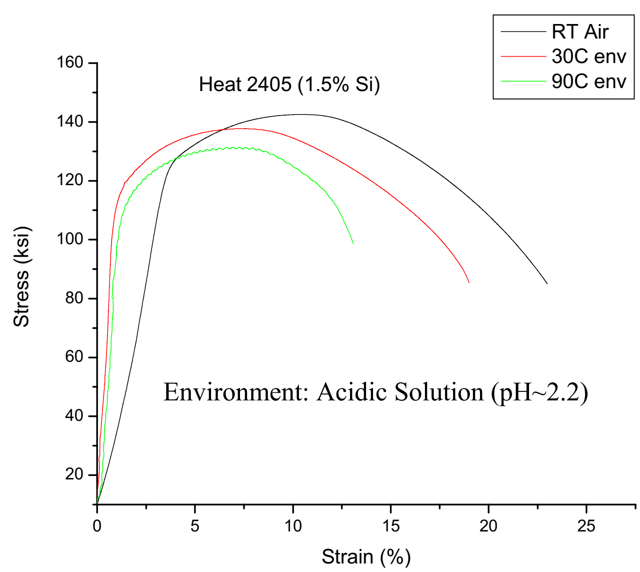
The localized corrosion susceptibility of these materials has also been investigated by cyclic potentiodynamic polarization (CPP) technique. The CPP testing has enabled the development of an understanding on localized corrosion behavior in terms of the corrosion potential (E_{corr}) and the critical pitting potential (E_{pit}).

SEM has been used to analyze the extent and morphology of failure at the primary fracture surface of the specimens tested under a slow-strain-rate (SSR) condition. The cracking susceptibility has been expressed in terms of the true failure stress, time to failure and ductility parameters (%El and %RA).

RESEARCH ACCOMPLISHMENTS

- The tensile data indicates that the magnitudes of both YS and UTS were gradually reduced with increasing temperature, as anticipated. However, there was a gradual drop in the failure strain in the temperature regime of ambient to 400ºC.

- The gradual reduction in failure strain in the susceptible temperature regime has often been cited to be the result of work hardening resulting from the diffusion of interstitial solute elements onto the dislocations near the grain boundaries. This phenomenon, known as dynamic strain ageing, is also a function of strain rate used during plastic deformation under tensile loading.
- At 550ºC, there was an increase in ductility in terms of failure strain, possibly due to enhanced plastic flow even under an identical strain rate of $5\text{x}10^{-4}$ s^{-1}.
- In view of the minimum failure strain noted at 400ºC within the susceptible temperature regime (ambient to 400ºC) for all four alloys, testing was performed under three additional strain rates of 10^{-2}, 10^{-3} and 10^{-4} s^{-1} at this temperature. The resultant data indicate that the maximum failure strain at this temperature was observed at a strain rate of 10^{-4} s^{-1}, suggesting that this could be the critical strain rate at or below which the concept of DSA may not be prevalent.
- The results of SSR testing in an acidic solution (pH~2.2) suggest that the cracking susceptibility was enhanced at 90ºC in terms of the reduced time to failure and failure strain.
- SEM study on self-loaded C-Ring specimens revealed a separation of grains possibly due to the decohesion of surface layers resulting from their interaction with the molten metal (LBE). Intergranular brittle crack was seen on the convex side of this specimen, which also revealed the presence of lead, as observed by energy dispersive spectroscopy (EDS).



Stress-strain diagram in Slow-Strain-Rate testing.

ACADEMIC YEAR HIGHLIGHTS

- Thesis Generated:

  Harish Krishnamurthy, "Metallurgical and Corrosion Characterization of a Martensitic Stainless Steel as a function of Silicon Content," M.S. Thesis, December 2005.

- Conference Publications:

  P. Kumar, D. Maitra, A.K. Roy, "Metallurgical and Corrosion Studies of Modified T91 Grade Steel," MRS Spring Meeting, San Francisco, CA, April 2006.

  P. Kumar, D. Maitra, S. Kohir, "Metallurgical and Corrosion Characterization of T91 Grade Steel versus Silicon Content," ANS Students' Conference, RPI, NY, April 2006.

  P. Kumar, D. Maitra, H. Krishnamurthy, "Effect of Silicon Content on Modified T91 Grade Steel for Nuclear Application," ASM Heat Treat Conference, Poster Presentation, Pittsburgh, PA, September 2005.

  P. Kumar, D. Maitra, H. Krishnamurthy, "Effect of Silicon Content on Metallurgical and Corrosion Properties of Martensitic Stainless Steel," ANS Students' Conference, Columbus, OH, April 2005.

FUTURE WORK

- Tensile properties evaluation of materials at 300ºC under different strain rate conditions.
- Comparative analyses of tensile data at 300 and 400ºC under different strain rates.
- Determination of dislocation density under different experimental conditions as a function of Si content.
- Analyses of metallurgical microstructures as a function of Si content and metallurgical variables.
- Determination of the temperature dependence on critical pitting potentials, ductility parameters and true failure stress in corrosion studies.
- The determination of the effect of controlled electrochemical potential on the SCC susceptibility.
- Performance of charpy impact testing to determine the ductile-to-brittle transition temperature.
- Determination of the effect of radiation on the tensile properties of T91 grade steels.
- Characterization of fracture toughness (compact tension) and crack growth rate (double cantilever beam).

Research Staff

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