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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

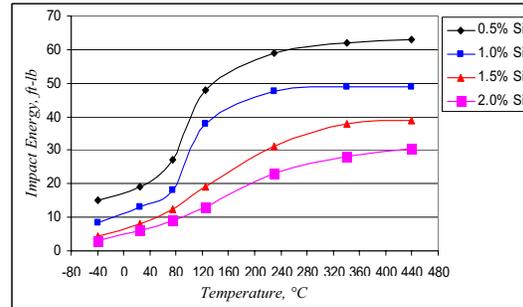
# Effect of Silicon Content on the Corrosion Resistance and Radiation-Induced Embrittlement of Materials for Advanced Heavy Liquid Metal Nuclear Systems

A.K. Roy

## BACKGROUND

This task is focused on the evaluation of the effects of silicon content on both the corrosion behavior and radiation-induced embrittlement of martensitic stainless steels having compositions similar to that of modified 9Cr-1Mo steel, also known as T91 grade steel. T91 grade steel was selected to be a candidate structural material to contain molten lead-bismuth eutectic (LBE), which can act both as a target material and a coolant during the spallation process. The operating temperature during this process may range from 420-550 °C. Thus, moderate tensile strength of the containment material (T91) is a major requirement.

The beneficial effects of Si on both the metallurgical and corrosion properties of chromium-molybdenum (Cr-Mo) steels have previously been demonstrated at UNLV. Therefore, additions of Si ranging from 0.5-2.0 weight percent (wt%) was attempted in this investigation to explore Si effect on both the high temperature tensile properties and corrosion behavior of T91 grade steel. Corrosion studies in the presence of molten LBE could not be performed due to a lack of proper experimental facilities at UNLV. Therefore, detailed corrosion studies involving Si-containing T91 grade steels were performed in an aggressive aqueous solution of acidic pH. Further, significant efforts have



Impact Energy (ft-lb) vs. Temperature (°C)

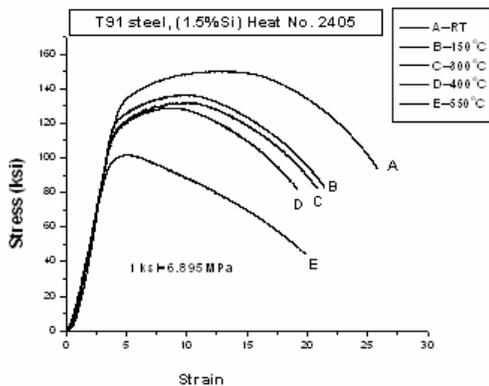
been made to determine both the impact and fracture toughness of the tested materials as a function of Si content.

## RESEARCH OBJECTIVES AND METHODS

Four heats of T91 grade steel having Si levels of 0.5, 1.0, 1.5 and 2.0 wt% were custom-melted by a vacuum-induction-melting practice. They were subsequently processed and thermally-treated to achieve fully-tempered martensitic microstructures. These materials were then machined to fabricate desired types of specimens for evaluation of tensile properties, impact toughness, fracture toughness, resistance to localized corrosion, stress corrosion cracking (SCC), and crack propagation behavior. Limited tensile testing was also performed on T91 grade steels under different levels of radiation. Numerous state-of-the-art experimental techniques were employed to evaluate the desired properties. The relevant experimental techniques have been described in previous annual reports. The significant results obtained during the past fiscal year are summarized below.

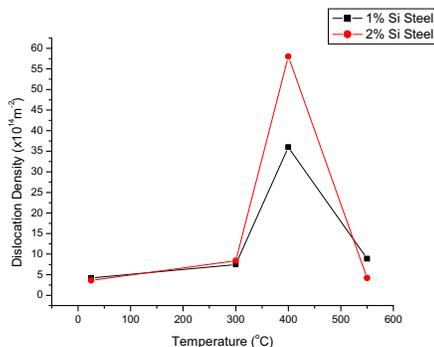
## RESEARCH ACCOMPLISHMENTS

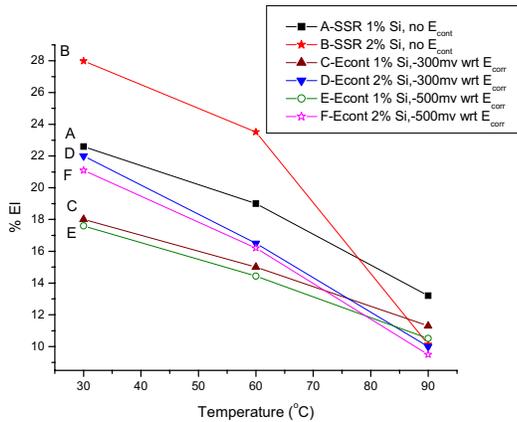
- The results of tensile testing indicate that the magnitude of failure strain ( $\epsilon_f$ ) was gradually reduced with increasing temperature within a susceptible temperature range, irrespective of the Si content. Simultaneously, serrations were also noted in the engineering stress vs. strain diagrams.
- The reduced  $\epsilon_f$  values and the occurrence of serrations within a specific temperature regime can be attributed to a metallurgical phenomenon known as Dynamic Strain Ageing (DSA). Irrespective of the Si content, the susceptibility to DSA was predominant at temperatures ranging from ambient to 400°C.
- The DSA phenomenon, as seen in this investigation, is commonly associated with the diffusion of solute elements into the matrix of the material at elevated temperatures, thus impeding the movement of dislocations through the matrix and grain boundaries. Such reduction in dislocation mobilities can significantly impair the plastic deformation, which is manifested by reduced  $\epsilon_f$  values, as seen in this study.



Stress-Strain Diagrams of T91 Steel with 1.5 wt% Si

Dislocation Density vs. Temperature (°C)





Variation of %EI with temperature for steels (1 and 2 wt% Si), with and without cathodic  $E_{cont}$ .

- A maximum dislocation density ( $\rho$ ), determined from the transmission electron micrographs, was seen at 400°C, irrespective of Si content.
- The work hardening index ( $n$ ) and activation energy for diffusion are two key parameters influencing the DSA behavior of engineering materials. Simultaneously, both temperature and strain rate can influence the DSA behavior. The variation of  $n$  with temperature at a strain rate of  $5 \times 10^{-4} \text{ sec}^{-1}$  is shown in the table below. A gradual increase in the  $n$  value was observed at temperatures up to 400°C, as expected.
- A longer activation time using an electron beam resulted in reduced ductility in terms of  $e_f$ .
- The presence of higher Si content in T91 grade steel resulted in reduced impact energy and higher ductile-brittle transition temperature, indicating reduced impact resistance.
- The susceptibility to SCC was enhanced at more cathodic (active) controlled potentials ( $E_{cont}$ ) and higher testing temperature, implying a synergistic effect of cathodic potential and temperature on SCC.
- The morphology of failure in double-cantilever-beam specimen used in SCC testing was characterized by a combination of striations (fatigue), SCC (intergranular/transgranular), and fast fracture (dimples).

Variation of  $n$  with Temperature (RT: Room Temperature)

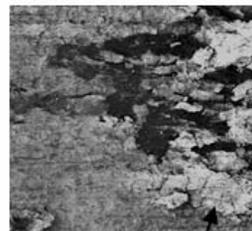
Heat no. / Temp(°C)	RT	150	300	400	550
2403 (0.5%Si)	0.1643	0.1698	0.1784	0.1984	0.1432
2404 (1.0%Si)	0.1716	0.1794	0.1945	0.2143	0.1564
2405 (1.5%Si)	0.1586	0.1702	0.1794	0.1802	0.1642
2406 (2.0%Si)	0.1669	0.1709	0.1772	0.1997	0.0994

## ACADEMIC YEAR HIGHLIGHTS

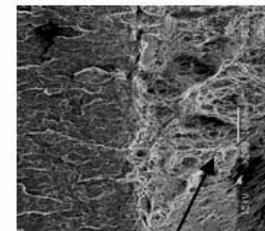
- ♦ S. Kohir, "Tensile Properties and Environmental Degradation of martensitic and Austenitic Stainless Steels," ISRS-2006, Madras, India, December 18-20, 2006.
- ♦ P. Kumar, D. Maitra, and A. Roy, "Temperature and Silicon Content Effects on Tensile deformation of T91 Grade Steel," Society for the Advancement of Materials and Process Engineering, Fall meeting, Dallas, TX, November 2006.
- ♦ D. Maitra, P. Kumar, and A. Roy, "The Role of Silicon Content on Tensile and Corrosion Properties of T91 Grade Steels," MS&T, Fall meeting, Cincinnati, OH, October 2006.
- ♦ D. Maitra, A. Roy, "Environmental Cracking and Localized Corrosion of T91 Grade Steel with Different Silicon Content," AMPT 2006, Las Vegas, NV, July 2006.
- ♦ P. Kumar, A. Roy, "Tensile Properties of T91 Grade Steel as a Function of Silicon Content," AMPT-2006, Advances in Materials and Processing Technology, Las Vegas, NV, July 2006.
- ♦ P. Kumar, D. Maitra, and A. Roy, "Metallurgical and Corrosion Studies of Modified T91 Grade Steel," *Materials Research Symposium Proceedings*, v 929, pp 149-154, 2006.

## FUTURE WORK

Stress corrosion cracking will be evaluated under anodic  $E_{cont}$ , dynamic strain ageing will be characterized by transmission electron microscopy, and fracture toughness will be evaluated.



Precrack-SCC interface



SCC-Fast Failure interface



Scanning electron microscope micrographs of double-cantilever beam specimens with 0.5 wt% Si subjected to SCC testing at 100°C in acidic solution for 30 days.

## Research Staff

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