

# *Tensile and Low Cycle Fatigue Behavior of Modified 9Cr–1Mo steel*



Thesis submitted in partial fulfillment  
for the Award of degree

**DOCTOR OF PHILOSOPHY**

By

**Preeti Verma**

**DEPARTMENT OF METALLURGICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY  
(BANARAS HINDU UNIVERSITY)  
VARANASI-221005**

---

---

## **CERTIFICATE**

---

---

It is certified that the work contained in the thesis titled "*Tensile and Low Cycle Fatigue Behavior of Modified 9Cr-1Mo Steel*" by "*Preeti Verma*" has been carried out under our supervision and this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive, Candidacy and SOTA.

**Dr. Vakil Singh, Professor (Emeritus)**  
**(Supervisor)**

Department of Metallurgical Engineering  
Indian Institute of Technology  
(Banaras Hindu University)

**Prof. N. C. Santhi Srinivas**  
**(Co-Supervisor)**

Department of Metallurgical Engineering  
Indian Institute of Technology  
(Banaras Hindu University)

---

---

## **DECLARATION BY THE CANDIDATE**

---

---

I, "*Preeti Verma*", certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of "*Dr. Vakil Singh, Professor (Emeritus) and Prof. N. C. Santhi srinivas*" from "*July 2012*" to "*June 2016*", at the "*Department of Metallurgical Engineering*", Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc.*, reported in journals, books, magazines, reports dissertations, theses, *etc.*, or available at websites and have not included them in this thesis and have not cited as my own work.

Date

Place

**Preeti Verma**

## **CERTIFICATE BY THE SUPERVISORS**

It is certified that the above statement made by the student is correct to the best of our knowledge.

**Dr. Vakil Singh, Professor (Emeritus)**  
**(Supervisor)**

**Prof. N. C. Santhi Srinivas**  
**(Co-Supervisor)**

Department of Metallurgical Engineering  
Indian Institute of Technology  
(Banaras Hindu University)

Department of Metallurgical Engineering  
Indian Institute of Technology  
(Banaras Hindu University)

**Head**

Department of Metallurgical Engineering  
Indian Institute of Technology  
(Banaras Hindu University)

---

---

# **COPYRIGHT TRANSFER CERTIFICATE**

---

---

**Title of the Thesis:** *“Tensile and Low Cycle Fatigue Behavior of Modified 9Cr–1Mo Steel”*

**Name of the Student:** *Preeti Verma*

## **COPYRIGHT TRANSFER**

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the *"PhD Degree"*.

Date:

Place:

**Preeti Verma**

**Note:** However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

# Chapter 8

## Summary and Future Work

## **8.1 Introduction**

This Chapter of the thesis entitled “Tensile and Low Cycle Fatigue Behavior of Modified 9Cr–1Mo steel” summarizes the important observations and also includes suggestions for future research.

## **8.2 Summary**

Systematic investigation was carried out on tensile and low cycle fatigue behavior of modified 9Cr–1Mo steel at different temperatures and strain rates. The important observations made on different aspects are listed at the end of respective chapters and major findings related to the work are given here. The major findings is divided into two parts and summarized below:

### ***8.2.1 Tensile Behavior***

The modified 9Cr-1Mo steel in normalized and tempered condition is found to exhibit dynamic strain ageing over the temperature range from 250–400 °C, based on the its anomalous behavior such as plateau/peak in yield, tensile strength, minima in ductility, serrations in stress–strain curves, negative strain rate sensitivity and Snoek peak in internal friction. Typical features of dislocations; like bowing and loop formation are also observed in the region of DSA. Nitrogen element was identified responsible for the occurrence of DSA.

The typical rosette fracture with central fibrous zone, radial cracking at different angular interval resulting from longitudinal splitting and very fine shear lip zone is observed in the temperature range from -70 to 80 °C. Longitudinal splitting occurred due to formation of voids and their coalescence around the carbides particles along the

prior austenite grain/lath boundaries and the stress distribution in the necked region. This fracture is found to be independent of texture and strain rate.

### ***8.2.2 Low Cycle Fatigue Behavior***

The modified 9Cr–1Mo steel exhibits cyclic softening irrespective of strain amplitude, strain rate and temperature. However, inverse dependence of strain rate on cyclic stress response, fatigue life, plastic strain amplitude and fatigue crack propagation is observed. This suggests occurrence of DSA under cyclic deformation at 300 °C.

Cyclic softening is attributed to transformation of tempered lath martensite structure to cell structure. Also there is decrease in dislocation density at room temperature, in addition to above factors annihilation of dislocations at 300 °C. Several other factors contributed to LCF behavior of this steel at 600 °C such as coarsening of carbides, grain rotation and annihilation of dislocations. The formation of cell structure is found to be strongly dependent on the strain amplitude. It increased with increase in strain amplitude. The modified 9Cr–1Mo steel exhibits transition from non-Masing to Masing behavior at  $\pm 0.375\%$  at RT and 300 °C and it is associated with change in the equiaxed cell structure at low strain amplitudes to elongated cell structure at high strain amplitudes.

Inter striation spacing is found to increase with increase in strain amplitude at all the test temperatures. Oxidation of the steel is observed at 600 °C. The reduction in fatigue life at low strain rate may be due to increase in the severity of the oxidation at 600 °C.

### **8.3 Suggestions for Future Work**

The following suggestions are made for future investigations based on the present investigation:

- Simulation of the rosette fracture in tensile deformation.
- Prediction of low cycle fatigue results at different temperatures using different models.
- Creep fatigue interaction study of this material at different temperatures.
- Examination of the microstructural stability.