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# Effects of Long-Term Thermal Aging on Mechanical Properties and Microstructural Evolution of 17-4 PH Stainless Steel in Simulated Thermal Conditions for Nuclear Applications

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## 1. Introduction

17-4 PH stainless steel is widely used in nuclear reactors and spent nuclear fuel storage systems due to its high strength and corrosion resistance. However, prolonged exposure to elevated temperatures leads to microstructural changes affecting its mechanical properties. These changes primarily result from precipitation phenomena, phase transformations, and carbide formations that lead to embrittlement. While previous studies have explored the effects of thermal aging, there remains a gap in understanding the long-term evolution of microstructure and its influence on toughness degradation at nuclear-relevant temperatures [1,2]. Furthermore, limited studies have analyzed the combined effects of spinodal decomposition and G-phase formation over prolonged periods. This study focuses on thermal aging at 300°C–400°C for extended durations, analyzing hardness, tensile properties, and impact toughness in correlation with microstructural transformations. The findings contribute to the fundamental understanding of long-term material behavior in nuclear environments.

## 2. Materials and Experiment

### *2.1 Test materials*

The 17-4 PH SS used in this study was subjected to solution heat treatment at 1050°C followed by aging at 621°C for four hours, resulting in a martensitic matrix containing fine Cu precipitates. The as-received material exhibited a typical lath martensitic structure with an average grain size of approximately 14.6 µm as shown in Fig. 1.

### *2.2 Experimental conditions and procedure*

The specimens were aged at 300°C, 350°C, and 400°C for durations of 1,000 to 12,000 hours to simulate extended service conditions. Hardness, tensile, and Charpy impact tests were performed in accordance with ASTM standards [3,4]. Microstructural analysis was conducted using TEM with energy-dispersive X-ray spectroscopy (EDS) mapping. The results obtained provide a comprehensive understanding of the influence of thermal aging on both mechanical and microstructural characteristics.

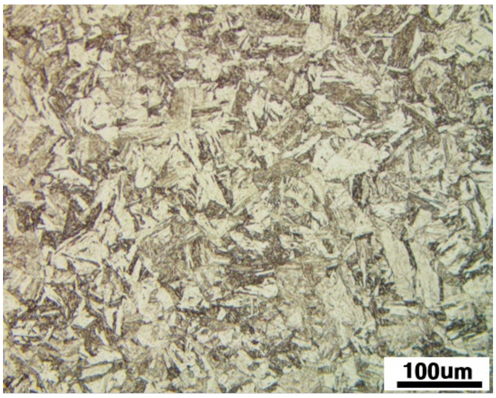

Fig. 1. Microstructure of 17-4 PH SS used in this study.

## 3. Results and Discussion

### *3.1 Hardness and tensile properties*

Hardness increased with aging time due to Cu precipitation and spinodal decomposition, reaching a peak at approximately 10,000 hours at 400°C, followed by a decline attributed to G-phase coarsening. Tensile strength followed a similar trend, with 400°C showing the most significant degradation after 10,000 hours as presented in Fig. 2. The observed softening at higher temperatures suggests a transition in the aging mechanism, which could be linked to phase transformations.

### *3.2 Impact toughness*

Impact energy reduced significantly at 350°C and 400°C due to embrittlement caused by spinodal decomposition and G-phase precipitation. The most pronounced degradation occurred after 5,000 hours at 350°C, coinciding with the onset of G-phase formation at the Cu/martensite interface. This finding is crucial as it highlights the embrittlement risk associated with prolonged exposure to moderate to high temperatures in nuclear environments.

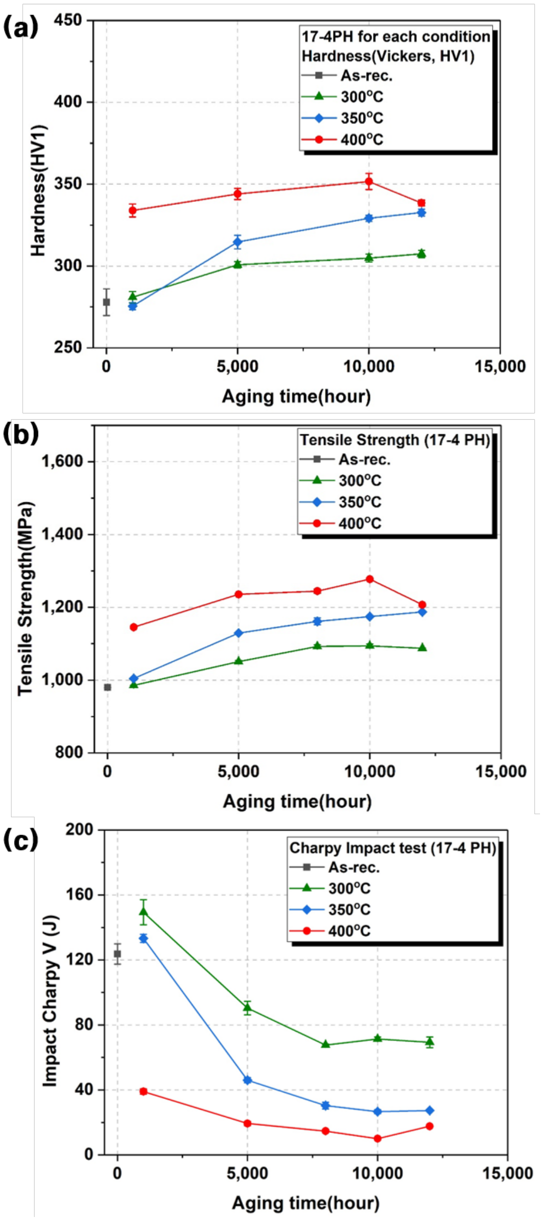


Fig. 2. Mechanical properties of (a) hardness, (b) tensile strength and (c) charpy impact energy for 17-4 PH SS at different aging temperature and time.

### *3.3 Microstructural evolution*

TEM analysis revealed spinodal decomposition at all temperatures, with Cr-rich precipitates forming at Cu/martensite interfaces. At 350°C and 400°C, G-phase precipitation was observed, intensifying embrittlement. The progressive growth of the G-phase altered the mechanical behavior, accelerating toughness loss. After 12,000 hours at 400°C, coarsening of the G-phase led to softening as Cu precipitates lost coherence with the martensitic matrix, reducing the embrittlement effect.

### *3.4 Softening Mechanisms at 400°C*

After 12,000 hours of aging at 400°C, a reduction in hardness and strength was observed. TEM analysis revealed that the G-phase coarsened and encroached upon Cu precipitates, causing a loss of coherence with the martensitic matrix. This phenomenon explains the observed softening and suggests a complex interplay between Cu precipitation, G-phase formation, and martensitic transformations over prolonged aging periods.

## 4. Conclusions

This study examined the thermal aging behavior of 17-4 PH SS at 300°C–400°C for up to 12,000 hours, revealing the following:

- Hardness and strength increased initially due to spinodal decomposition and Cu precipitation but declined after prolonged exposure at 400°C due to G-phase coarsening.
- Impact toughness degradation was most significant at 350°C and 400°C due to G-phase precipitation, which contributed to embrittlement.
- Spinodal decomposition was the dominant mechanism at 300°C, whereas both spinodal decomposition and G-phase formation influenced aging at higher temperatures, altering mechanical behavior.
- The coarsening of the G-phase at 400°C after 12,000 hours resulted in softening, indicating a potential long-term trade-off between hardness and toughness, which must be considered for nuclear applications.

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