Effect of Heat Treatment on ODS Steels for Tokamak Fusion Reactors

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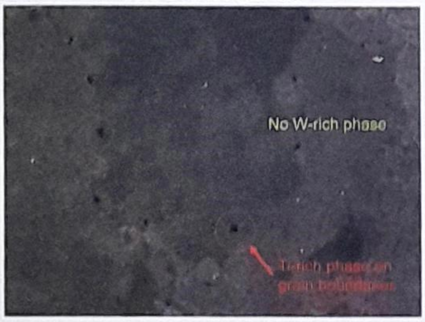
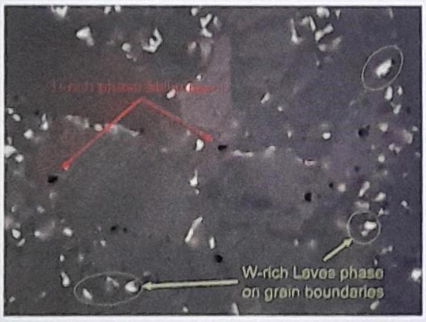
Introduction

Tokamak reactor efficiency is improved by operating at higher temperatures, and the D-T fusion reaction produces a high flux of 14 MeV neutrons. These two factors produce an incredibly demanding environment for materials to withstand. Since the structural components of a reactor will be either life-limiting or very expensive to replace, it is essential that the materials used are resistant to radiation-induced hardening and to creep at high temperature and high stress. Oxide dispersion strengthened (ODS) steels are candidates for fusion structural materials. A fine dispersion of Y_2O_3-based nanoparticles (radius <5 nm, number density ~10^{24}-10^{25} m^{-3} [1]) provide effective sinks for neutron cascade defects and can strongly pin dislocations, resulting in excellent high temperature creep resistance and much slower accumulation of radiation-induced damage. To ensure the best material is selected to construct reactors in the near future (e.g., STEP), it is important to understand how the microstructures and properties of ODS steels change when exposed to high temperatures for prolonged periods.

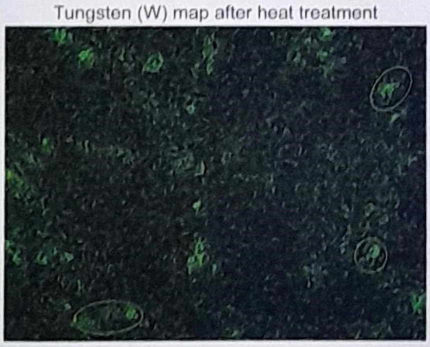
Before heat treatment



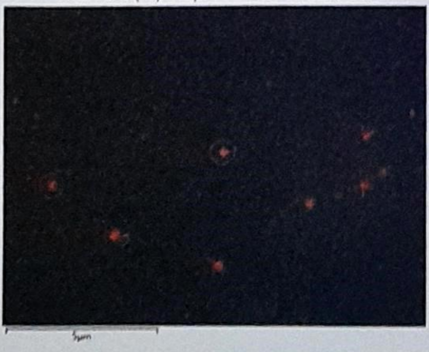
After heat treatment



Tungsten (W) map after heat treatment

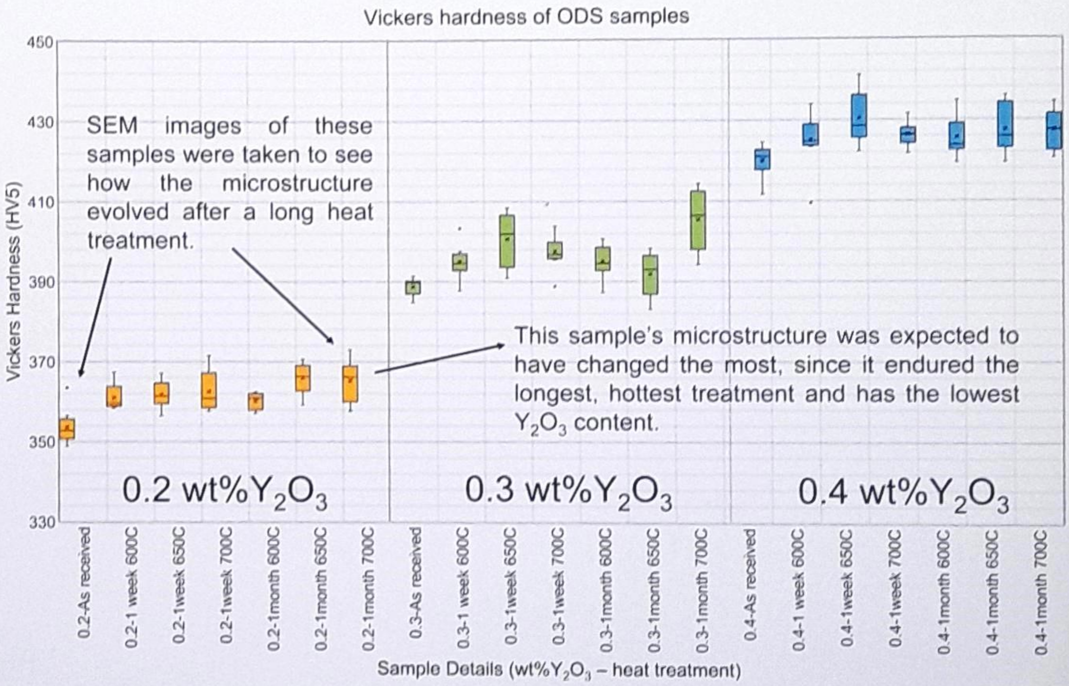


Titanium (Ti) map after heat treatment



Experiment overview

The Vickers hardness (HV5) of 21 different ODS steel samples were measured to investigate the effect of heat treatment on their mechanical properties. Some microstructures were analysed using scanning electron microscopy (SEM).



Results

It is evident that the Y_2O_3 content is the most important factor for determining hardness. The as-received samples also appear softer than all the heat-treated samples of the same composition. This could be due to the formation of $(Fe,Cr)_2W$ (Laves phase) at the grain boundaries. TiO is also present at grain boundaries, but the proportion doesn't change noticeably after ageing. There is no clear correlation between hardness and the heat treatment used.

Though the presence of the W-rich Laves phase doesn't have as great of an effect on hardness as Y_2O_3 concentration, it could promote intergranular fracture which would decrease the ductile-brittle transition temperature (DBTT). Neutron irradiation could also significantly impact how the Laves phase nucleates and grows.

Conclusions

- Y_2O_3 content affects hardness significantly more than heat treatment parameters.
- $(Fe,Cr)_2W$ Laves phase forms on thermal ageing, which hardens the material.
- TiO volume fraction remains low after heat treatment.
- Effect of the different heat treatments used is unclear.

Suggestions for future work

- Investigate Laves phase formation:
  - SEM imaging of 1 week and 600/650°C samples. Does it form quickly and saturate?
  - Carry out the same experiment on alloys with lower W content.
- Vickers indentation of samples with longer heat treatments.
- Charpy impact testing of all treatments to investigate DBTT and fracture properties.

References

[1] S. Ukai, N. Oono-Hori, S. Ohtsuka, "Oxide Dispersion Strengthened Steels" in *Comprehensive Nuclear Materials 2nd edition*, vol. 3, Elsevier Ltd., ch. 3 sec. 3.08, pp. 255-92

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