Radiation Tolerant Materials for Advanced Nuclear Reactors

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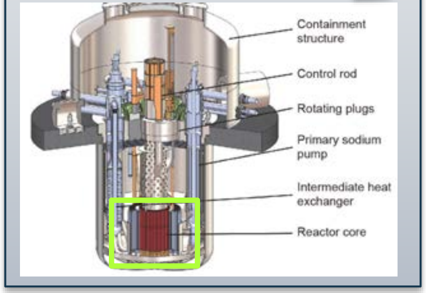
Materials Considerations for Advanced Nuclear Reactors

- Advanced nuclear energy is a **clean energy** option that can provide an abundance of **low carbon electricity**.
- The International Energy Agency projects that "without nuclear investment, **achieving a sustainable energy system will be much harder**."
- However, **advanced reactors' operability and lifetimes are limited** by the current capabilities of steel structural materials to withstand the harsh environment of the reactor cores.
- For these reactors to be viable, these **materials issues must be overcome**.

Core Structural Materials must withstand:

High temperature (>500°C)
High radiation damage levels
High stress
Corrosion



If unmitigated, these effects will lead to reactor shutdown from material failure. The negative effects can be mitigated by designing core materials to contain a high density of ***fine, stable precipitates***.

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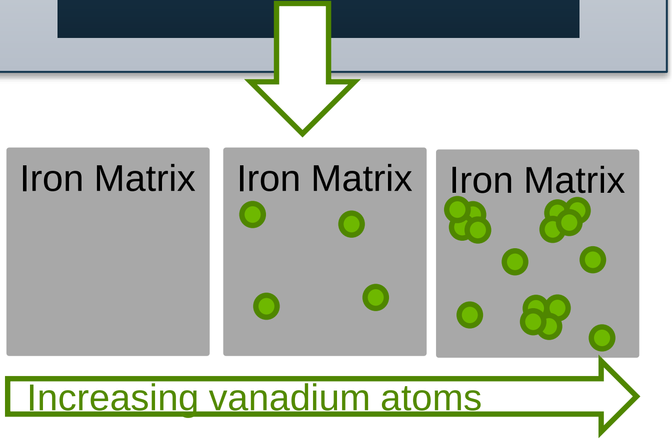
https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

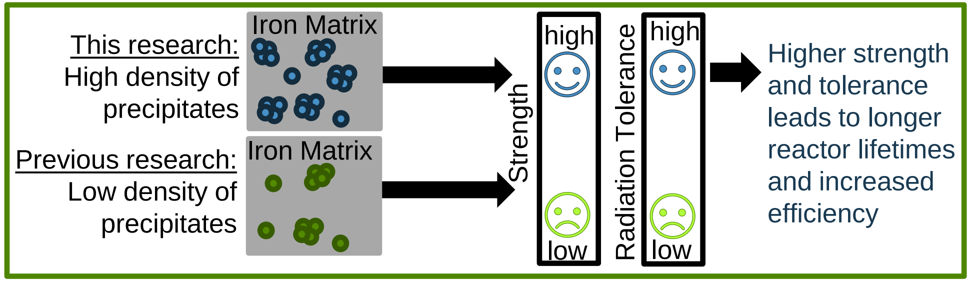
Background

- *Precipitates are a secondary phase embedded within the metallic microstructure.*
- *Precipitates in a metal are analogous to sugar in water: once you reach a certain limit of sugar, sugar clusters begin to precipitate out of the water (the matrix). Likewise, once a certain concentration of an element (such as vanadium) is reached in an iron matrix, the vanadium atoms will cluster into vanadium-rich precipitates. This is also dependent on temperature.*



Objective – Utilize Additive Manufacturing

- Previous research has sought to optimize methods of obtaining fine, stable precipitates, with limited success.
- This research focuses on **a novel method to engineer precipitate morphology and size distribution in a steel by optimizing parameters during 3D printing, also known as additive manufacturing (AM). The aim is to improve the radiation tolerance of the steel, thereby increasing the lifetime of advanced reactors.**



This research:
High density of precipitates

Previous research:
Low density of precipitates

Higher strength and tolerance leads to longer reactor lifetimes and increased efficiency

This experiment aims to:

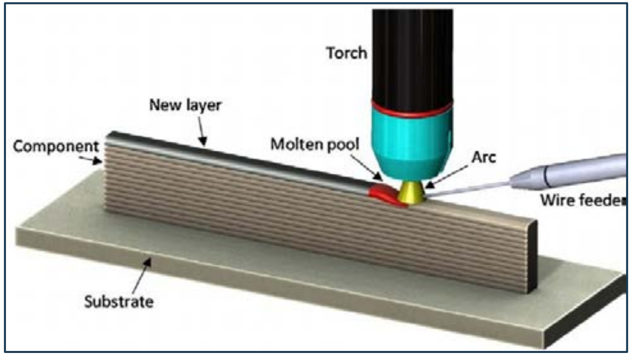
Assess AM for steel fabrication

Mimic or improve upon non-AM steel properties

Control precipitate structure with AM processing parameters

Method 1 – Build Samples with AM

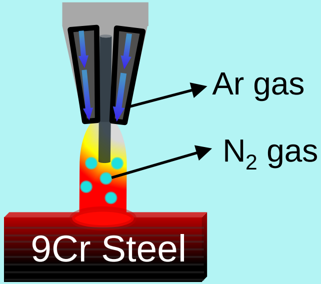
In a specific type of AM called wire arc, material in the form of a wire is deposited onto a substrate. The wire is then heated with an arc above its melting temperature, creating a molten pool. The heat source moves across a specified length, then begins a new layer. The molten material quickly solidifies, creating a unique microstructure.



Jin, W.; Zhang, C.; Jin, S.; Tian, Y.; Wellmann, D.; Liu, W. Wire Arc Additive Manufacturing of Stainless Steels: A Review. *Appl. Sci.* **2020**, *10*, 1563.

Two different builds of steel were fabricated. The steel wire initially contained 8.6% Cr, 0.08% Nb, 0.24%V, <1% of other elements, and a balance of Fe. Each build had a different shielding gas composition. Shielding gas circulates around the arc during fabrication and its composition is hypothesized to affect final precipitate composition, morphology, and size distribution in the build.

99% Ar-1% N_2 Shielding Gas (**Build 99/1**)



95% Ar-5% CO_2 Shielding Gas (**Build 95/5**)

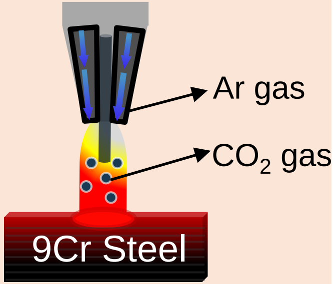
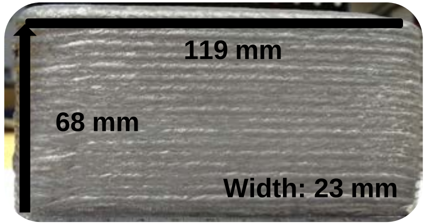


Photo of Build 99/1:



Background

Cr-Chromium
Nb-Niobium
V-Vanadium
Fe-Iron

Method 2 - Characterize AM Samples

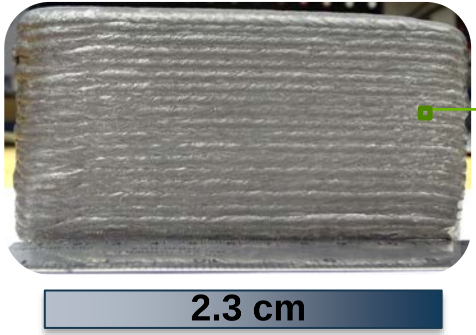
Small specimens must be made from the bulk sample for analysis

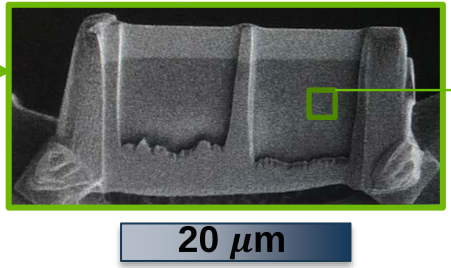
Use focused ion beam milling to create small specimens

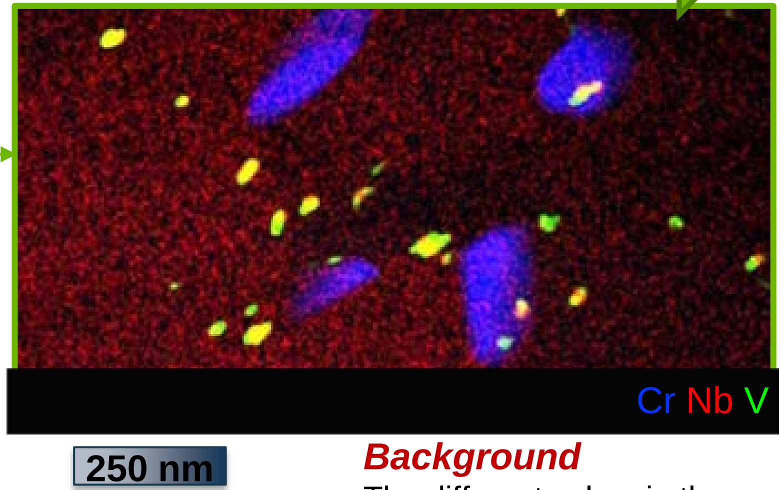
Investigate the precipitate structure of these samples using scanning transmission electron microscopy, which is analogous to optical microscopy except it uses electrons instead of light. The combined use of electron dispersive spectroscopy allows for chemical element analysis.

Order of Length Analysis

10^{-2} m → 10^{-7} m → 10^{-11} m







Background

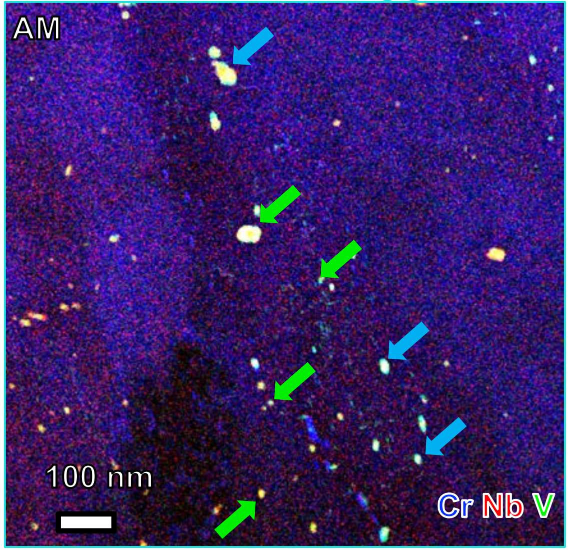
The different colors in the map represent different elements.

Results –Precipitates

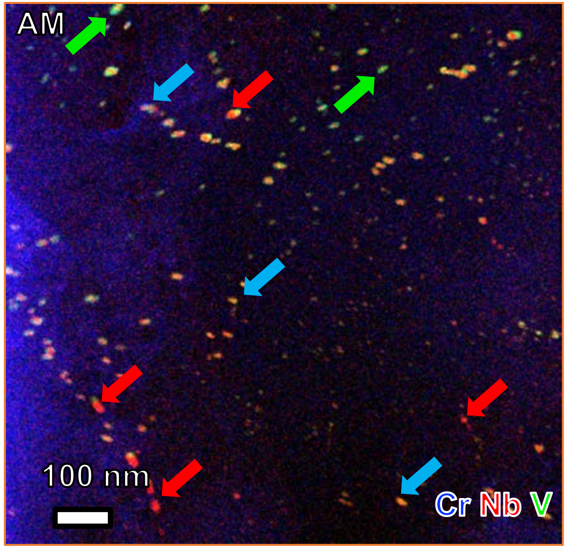
As hypothesized, three small MX-type precipitates formed in the AM materials (M: metal, X: carbon and/or nitrogen). Such small precipitates are preferred.

Green arrows: VN   Red arrows: Nb(C,N)   Blue arrows: (Nb,V)(C,N)

Build 99/1:
62% increase in N content from the N_2 additions to shielding gas



Build 95/5:
16% increase in C content from CO_2 additions to shielding gas



Parameter	AM	
Build	99/1	95/5
Mean Size (nm)	12±7	12±5
Number Density ($\times 10^{20}$ m^{-3})	14±3	20±4
Nb(C,N)	0%	5.7%
VN	51.5%	9.6%
(Nb,V)(C,N)	48.5%	79.6%

N_2 additions to the shielding gas did not significantly affect the precipitate sizes but **greatly affected the composition and morphology of the MX precipitates**, as compared to CO_2 gas additions

Results – Chemical Analysis of Precipitates

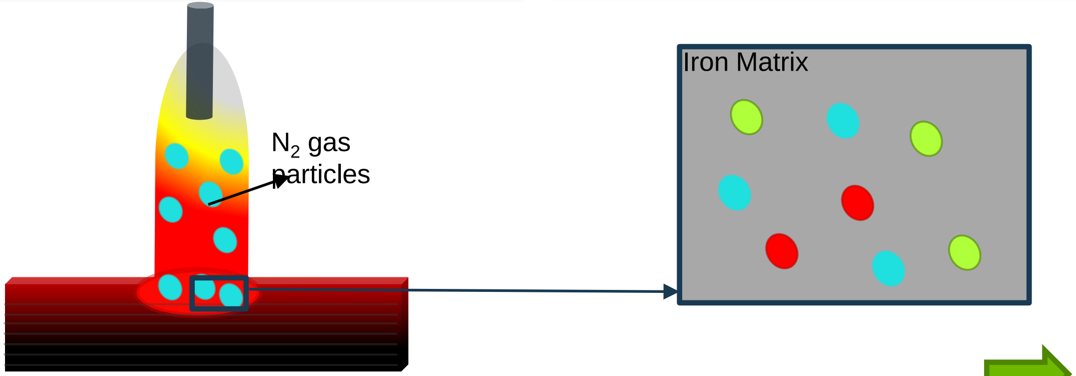
Why did the two builds show different types of precipitates?

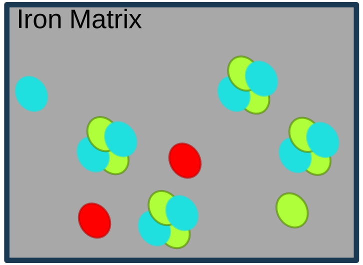
Take Build 99/1 as an example:

The N_2 particles are added to the shielding gas during AM fabrication.

N_2 particles are absorbed into the molten pool.

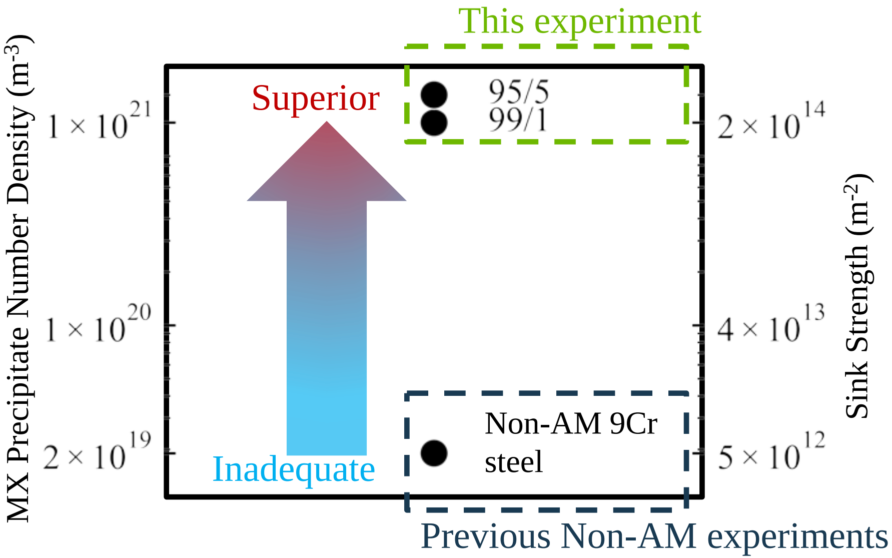
As the molten pool solidifies, the N_2 particles "attach" to other metallic elements to create precipitates. N has a greater affinity for V, therefore making more VN precipitates.





Build 95/5 had more C, which has a greater affinity for Nb. This caused more Nb-containing MX precipitates to form in Build 95/5.

Results- Precipitate Effect on Radiation Tolerance



Increase gained from shielding gas use in AM

- Sink strength evaluation is:
  - A method to preliminarily assess radiation tolerance: the higher sink strength, the higher radiation tolerance
  - A measurement of the amount of defect trapping and annihilation sites (such as precipitates) in a material, where the defects are created by impinging radiation in the core
  - Proportional to precipitate number density and precipitate size
- **A high sink strength can be achieved through an increase of precipitate number density, as was shown with this experiment:**
  - **A two-order magnitude increase in MX number density translated into a two-order magnitude increase in sink strength**

Clean Energy Education & Empowerment (C3E)

Conclusions

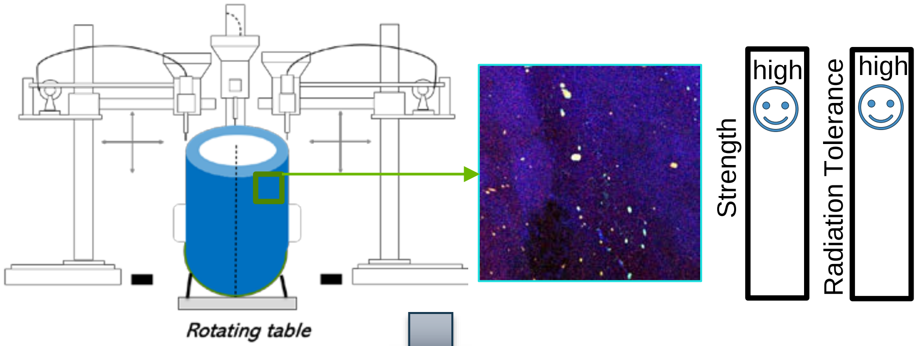
Successfully fabricated a 9Cr steel with AM

Improved upon non-AM 9Cr steel microstructure properties and radiation tolerance

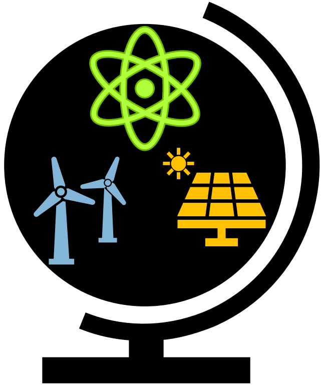
Proved ability to control MX precipitate chemistry and stability with shielding gas composition

Contributed significant findings for AM to be used in the development of advanced reactors.

AM being used to make a reactor pressure vessel

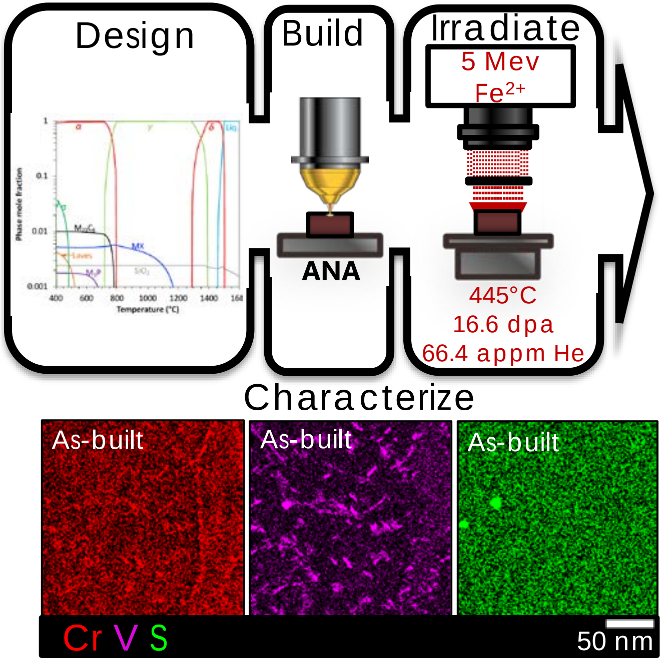


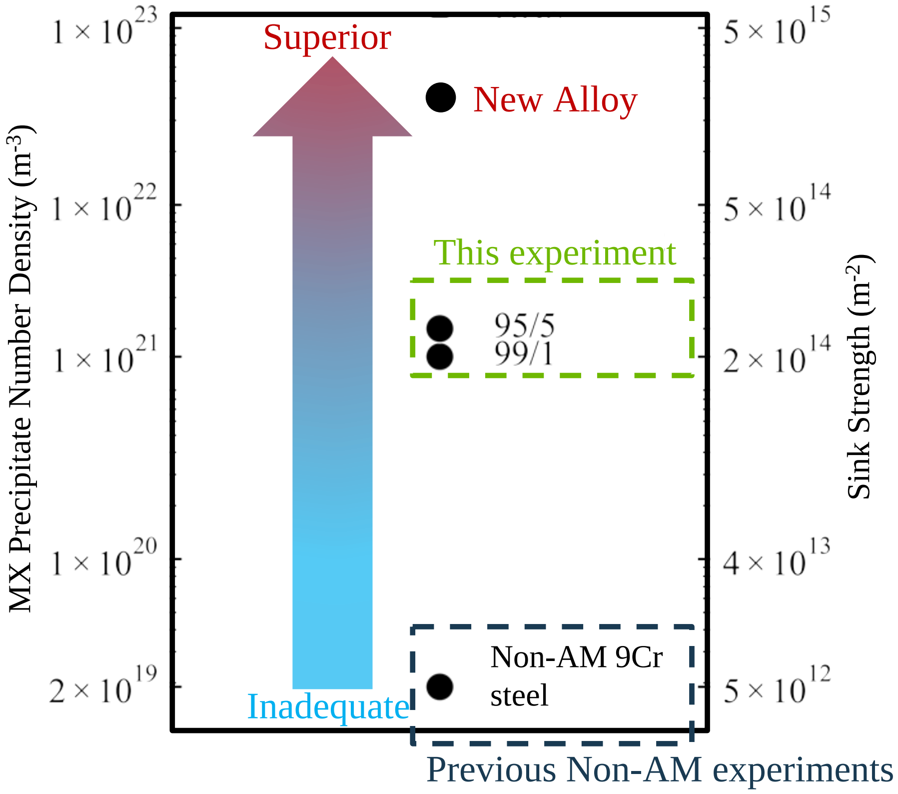
Lifetime of advanced reactors increased due to material improvements from AM, contributing to increased nuclear energy adoption and hence to a balanced, low carbon energy mix worldwide.



Future work

Apply knowledge from this experiment to a novel alloy fabricated with AM for increased radiation tolerance.





References

[1] S.J. Zinkle, J.T. Busby, Structural materials for fission & fusion energy, Mater. Today. 12 (2009) 12–19. https://doi.org/10.1016/S1369-7021(09)70294-9.

[2] K. Sawada, M. Taneike, K. Kimura, F. Abe, Effect of nitrogen content on microstructural aspects and creep behavior in extremely low carbon 9Cr heat-resistant steel, ISIJ Int. 44 (2004) 1243–1249. https://doi.org/10.2355/isijinternational.44.1243.

[3] F. Abe, Precipitate design for creep strengthening of 9% Cr tempered martensitic steel for ultra-supercritical power plants, Sci. Technol. Adv. Mater. 9 (2008). https://doi.org/10.1088/1468-6996/9/1/013002.

[4] R.L. Klueh, Elevated-Temperature Ferritic and Martensitic Steels and Their Application To Future, 2004.

[5] R.L. Klueh, D.R. Harries, High-Chromium Ferritic and Martensitic Steels for Nuclear Applications, 2001. https://doi.org/10.1520/MONO3-EB.

[6] P. Dubuisson, D. Gilbon, J.L. Séran, Microstructural evolution of ferritic-martensitic steels irradiated in the fast breeder reactor Phénix, J. Nucl. Mater. 205 (1993) 178–189. https://doi.org/10.1016/0022-3115(93)90080-I.

[7] L. Tan, L.L. Snead, Y. Katoh, Development of new generation reduced activation ferritic-martensitic steels for advanced fusion reactors, J. Nucl. Mater. 478 (2016) 42–49. https://doi.org/10.1016/j.jnucmat.2016.05.037.

[8] N. Sridharan, M.N. Gussev, K.G. Field, Performance of a ferritic/martensitic steel for nuclear reactor applications fabricated using additive manufacturing, J. Nucl. Mater. 521 (2019) 45–55. https://doi.org/10.1016/j.jnucmat.2019.04.020.

[9] N. Sridharan, K. Field, A Road Map for the Advanced Manufacturing of Ferritic-Martensitic Steels, Fusion Sci. Technol. 75 (2019) 264–274. https://doi.org/10.1080/15361055.2019.1577124.

[10] B. Arivazhagan, S. Sundaresan, M. Kamaraj, A study on influence of shielding gas composition on toughness of flux-cored arc weld of modified 9Cr-1Mo (P91) steel, J. Mater. Process. Technol. 209 (2009) 5245–5253. https://doi.org/10.1016/j.jmatprotec.2009.02.006.

[11] A.D. Brailsford, R. Bullough, The Theory of Sink Strengths, 302 (1981) 87–137.

Acknowledgments

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