

UKAEA-CCFE-PR(19)57

Paul James Barron, Alexander W Carruthers,  
Jonathan W Fellowes, Nick G Jones, Huw Dawson,  
Ed J Pickering

# **Towards V-based high-entropy alloys for nuclear fusion applications**

Enquiries about copyright and reproduction should in the first instance be addressed to the  
UKAEA  
Publications Officer, Culham Science Centre, Building K1/0/83 Abingdon, Oxfordshire,  
OX14 3DB, UK. The United Kingdom Atomic Energy Authority is the copyright holder.

# **Towards V-based high-entropy alloys for nuclear fusion applications**

Paul James Barron, Alexander W Carruthers, Jonathan W Fellowes, Nick G Jones, Huw Dawson, Ed J Pickering



Manuscript Number: SMM-19-1479

Title: Towards V-based high-entropy alloys for nuclear fusion applications

Article Type: Regular article

Section/Category: No, do NOT upload to First Look

Keywords: high-entropy alloys; refractory metals; transition metals

Corresponding Author: Mr. Paul James Barron,

Corresponding Author's Institution: University of Manchester

First Author: Paul James Barron

Order of Authors: Paul James Barron; Alexander W Carruthers; Jonathan W Fellowes; Nick G Jones; Huw Dawson; Ed J Pickering

Abstract: By mixing elements with favourable nuclear activation properties to create high-entropy alloys, it may be possible to create a material that can withstand a nuclear fusion environment while minimising the radioactive waste produced. Such a material could be used in the extreme thermal and irradiation conditions of a fusion blanket. A suite of previously unexplored V-Cr-Mn and V-Cr-Mn-Ti alloys have been fabricated then homogenised and the resultant microstructures and phases were characterised. Results demonstrate that single-phase body centred cubic solid solution microstructures can be formed in highly-concentrated alloys incorporating low-activation elements, which is promising for a fusion alloy development standpoint.

Suggested Reviewers: Daniel B Miracle  
Air Force Research Laboratory, Wright-Patterson AFB  
daniel.miracle@us.af.mil

Oleg N Senkov  
Air Force Research Laboratory, Wright-Patterson AFB  
oleg.senkov.ctr@us.af.mil

Takuya Nagasaka  
National Institute for Fusion Science, Japan  
nagasaka@nifs.ac.jp

Pengfei Zheng  
Southwestern Institute of Physics, China  
zhengpf@swip.ac.cn

Sundeep Mukherjee  
University of North Texas  
Sundeep.Mukherjee@unt.edu





The University of Manchester  
School of Materials  
University of Manchester  
Oxford Road, M13 9PL, UK  
Email: paul.barron@manchester.ac.uk

Dear Editors,

We are submitting our paper entitled '*Towards V-based high-entropy alloys for nuclear fusion applications*' to Scripta Materialia for your consideration.

In this work, we have designed and characterized a number of novel ternary V-Cr-Mn and quaternary V-Cr-Mn-Ti alloys. The aim of this work was to explore these compositions to determine suitability for applications in nuclear fusion, with a particular view for use in the blanket structure of a fusion reactor. We've used a variety of characterization techniques to elucidate the microstructures of the alloys.

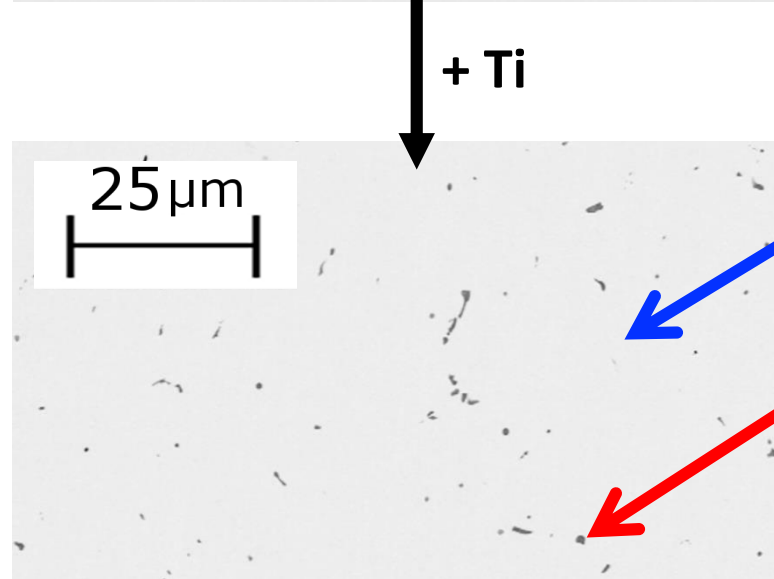
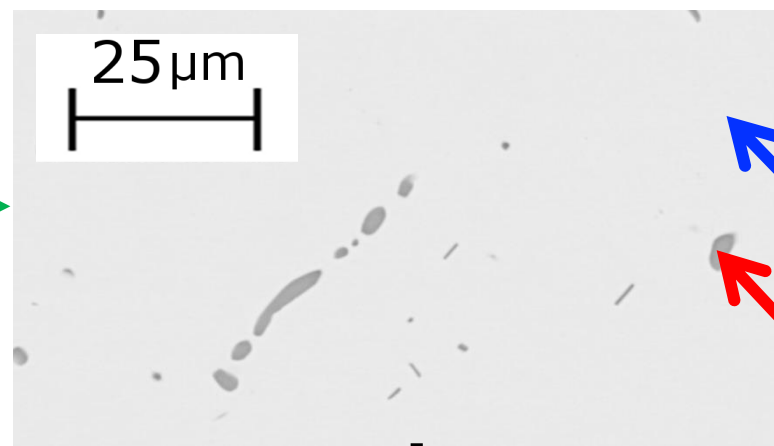
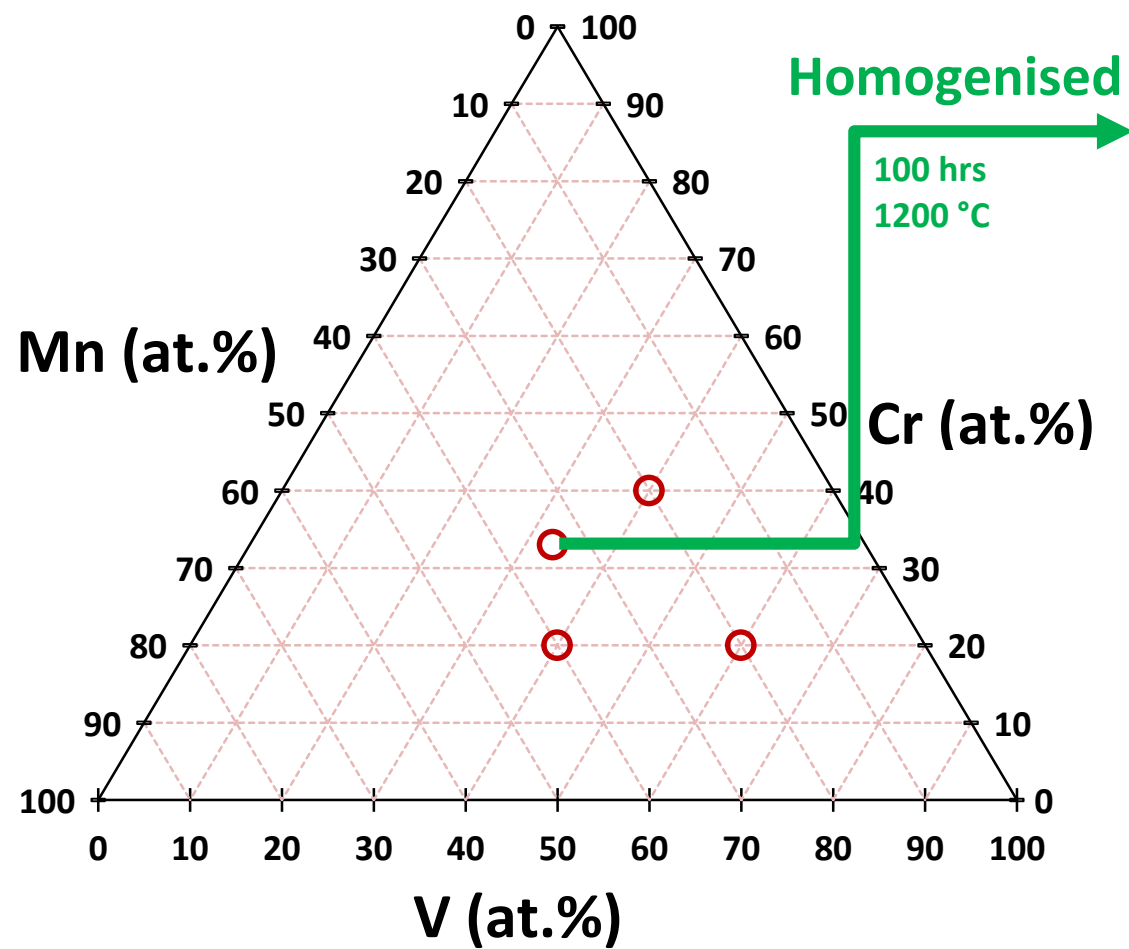
The following points state the key novelties associated with the work:

- A suite of V-Cr-Mn and V-Cr-Mn-Ti alloys are produced, heat-treated and characterized in detail. To the author's knowledge, these compositions have not been investigated previously. Both systems are generally poorly characterized.
- Our alloy design process is novel, in that we have used state-of-the-art predictions regarding elemental activation (from Gilbert *et al.*, paper reference [2]) to inform our choice of elements with a view to build towards HEA compositions.
- In both the as-cast and homogenised states, all the alloys comprised a single bcc matrix with small interstitial-containing precipitates. Achieving such stability in highly-concentrated multicomponent bcc systems is relatively rare, and is promising from a fusion alloy development standpoint.

This submission is original and is not being considered for publication elsewhere.

Yours sincerely,

Paul Barron  
PhD Student  
University of Manchester  
08/08/2019



Single bcc matrix  
Interstitial precipitates



1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

# Towards V-based high-entropy alloys for nuclear fusion applications

P.J. Barron<sup>a,\*</sup>, A.W. Carruthers<sup>a</sup>, J.W. Fellowes<sup>a</sup>, N.G. Jones<sup>b</sup>, H. Dawson<sup>c</sup>,  
E.J. Pickering<sup>a</sup>

<sup>a</sup>*Department of Materials, University of Manchester, Oxford Road, Manchester, M13 9PL, UK*

<sup>b</sup>*Department of Materials Science and Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, UK*

<sup>c</sup>*Culham Centre for Fusion Energy, Abingdon, OX14 3DB, UK*

---

## Abstract

By mixing elements with favourable nuclear activation properties to create high-entropy alloys, it may be possible to create a material that can withstand a nuclear fusion environment while minimising the radioactive waste produced. Such a material could be used in the extreme thermal and irradiation conditions of a fusion blanket. A suite of previously unexplored V-Cr-Mn and V-Cr-Mn-Ti alloys have been fabricated then homogenised and the resultant microstructures and phases were characterised. Results demonstrate that single-phase body centred cubic solid solution microstructures can be formed in highly-concentrated alloys incorporating low-activation elements, which is promising for a fusion alloy development standpoint.

*Keywords:* high-entropy alloys, refractory metals, transition metals

---

Nuclear fusion offers an alternative low-carbon energy source with potentially abundant fuel. However, fusion reactors must minimise the amount of harmful radioactive waste they produce in order to be considered a truly green energy source. This criteria necessitates the use of low-activation alloys, made from elements that will not remain radioactive for extended periods of time after exposure to fusion neutrons.

---

\*Corresponding author. Email: paul.barron@manchester.ac.uk.

The structural material of a fusion reactor blanket also has to face a variety of hostile conditions, including: extremes of neutron irradiation and temperature, transient loading from plasma instabilities, and corrosion from coolant systems[1]. These conditions necessitate the use of a material that is sufficiently strong, with good irradiation and creep resistance. The blanket will also require thousands of tons of material, precluding the use of extremely costly or scarce elements as significant alloying additions, or alloys that cannot be processed on large scales. Further restrictions are imposed by the aforementioned desire to use low-activation elements. A selection of elements that could be used in structural materials and the calculated time taken to reach low-level waste after use in a fusion reactor blanket are given in Table 1 [2]. It is apparent that certain elements such as Ni or Zr which are commonly used for nuclear structural applications would be unacceptable from a waste-management perspective.

Element	Time to safe handling / yrs	Element	Time to safe handling / yrs	Element	Time to safe handling / yrs
C	41	<b>V</b>	<b>12</b>	Zn	920
N	$5.6 \times 10^4$	<b>Cr</b>	<b>14</b>	Y	5.4
O	$1.1 \times 10^4$	<b>Mn</b>	<b>42</b>	Zr	$1.1 \times 10^6$
Mg	58	Fe	50	Nb	$2.5 \times 10^5$
Al	87	Co	170	Mo	$1.1 \times 10^6$
Si	10	Ni	$4.6 \times 10^5$	Ta	13
<b>Ti</b>	<b>6.3</b>	Cu	$1.2 \times 10^3$	W	14

Table 1: Calculated time taken to reach low-level waste after 14 years of pulsed operation in the DEMO reactor blanket shield. Elements used in this study have been highlighted. Data taken from [2]

Research efforts for fusion structural materials have been primarily focused on reduced activation ferritic-martensitic (RAFM) steels and vanadium alloys[3, 4, 5]. However, RAFM steels have a relatively low maximum operating temperature, limited by creep[6]. Their oxide dispersion strengthened counterparts offer improved high temperature performance but large scale processing is still an

1  
2  
3  
4  
5  
6  
7  
8  
9 issue[4]. V-based alloys containing other elements as minor ( $<10$  at.%) additions  
10 have been explored as an alternative to steels for fusion blanket applications[3].  
11 However, high-entropy alloys (HEAs) containing multiple low-activation ele-  
12 ments have received very little attention. A recent study by Ayyagari et al.[7]  
13 examined the TaTiVZrX system, but here we avoid Zr owing to its activation  
14 properties listed in Table 1. Investigation of more concentrated alloys cov-  
15 ering unexplored compositional space may yield materials that are more pro-  
16 cessable and have enhanced properties in comparison to the more conventional  
17 alloys. Other HEAs have shown surprising toughness[8] and irradiation swelling  
18 properties[9], so it is hoped that this work may form the basis for developing  
19 fusion alloys with improved properties such as a larger operating temperature  
20 window or easier processing.  
21  
22

23  
24  
25  
26  
27  
28 Due to the favourable activation properties of their constituent elements,  
29 alloys in the V-Cr-Mn ternary and V-Cr-Mn-Ti system were investigated. The  
30 nominal compositions are shown in Table 2. V and Cr were chosen because  
31 of their high melting points, which will allow for good creep performance at  
32 elevated temperatures in comparison to Fe-based alloys[6]. V and Cr show  
33 complete mutual solubility, forming a bcc phase at all compositions below the  
34 solidus[10]. A single bcc phase is considered highly desirable for adequate re-  
35 sistance to neutron irradiation swelling[11, 12, 13]. Additionally, Cr provides  
36 improved oxidation resistance in the binary system above around 30 wt.%[10].  
37 Such environmental resistance will be useful in limiting corrosion in service as  
38 well as in processing.  
39  
40  
41  
42  
43  
44

45  
46 Mn was chosen as an extra element in working towards a HEA composition  
47 because the binary V-Mn and Cr-Mn diagrams show a good solubility of Mn in  
48 both Cr and V[14]. The V-Cr-Mn ternary is not well characterized, but the one  
49 ternary diagram available in the literature seems to agree that Mn should have  
50 good solubility in an alloy containing V and Cr.[15] Although the power of the  
51 entropic stabilisation effect in HEAs is disputed [16, 17], the addition of Mn to a  
52 mixture of V and Cr will increase the configurational entropy of a solid solution  
53 of the elements and, therefore, should increase its high-temperature stability. It  
54  
55  
56  
57  
58

was hoped that the stability of the solid solution would be increased sufficiently to allow for the introduction of higher concentration of elements like Ti (see below) with less propensity to form damaging intermetallics, such as Laves phases (which appear in the Ti-Mn and Ti-Cr binary [14]) or secondary solid solutions.

Finally, Ti was added to act as an impurity getter in a similar manner to the behaviour found in V-Cr-Ti alloys[3, 18, 19] and interstitial free steels[20]. A reduction of interstitial solute concentration is desirable as they are known to cause embrittlement in vanadium alloys[21]. However, high quantities of both Cr and Ti are known to embrittle vanadium alloys[22, 23]. Furthermore, observation of the Ti-Mn and Ti-Cr binary phase diagrams suggests that Ti has low solubility in these two elements[14]. For these reasons, the amount of Ti added to the alloys was limited to 8 at.%.

Nominal				Measured (EPMA)			
V	Cr	Mn	Ti	V	Cr	Mn	Ti
60	20	20	-	$63.04 \pm 0.07$	$20.58 \pm 0.03$	$16.39 \pm 0.09$	-
40	20	40	-	$39.4 \pm 0.24$	$21.60 \pm 0.17$	$39.01 \pm 0.08$	-
40	40	20	-	$41.08 \pm 0.22$	$43.20 \pm 0.35$	$15.73 \pm 0.14$	-
33.33	33.33	33.33	-	$32.80 \pm 0.28$	$35.53 \pm 0.29$	$31.68 \pm 0.04$	-
33	33	33	1	$42.03 \pm 0.03$	$40.89 \pm 0.05$	$15.69 \pm 0.07$	$1.38 \pm 0.01$
32.67	32.67	32.67	2	$35.82 \pm 0.16$	$36.08 \pm 0.15$	$25.10 \pm 0.11$	$3.00 \pm 0.42$
32	32	32	4	$34.53 \pm 0.02$	$32.09 \pm 0.02$	$27.92 \pm 0.02$	$5.45 \pm 0.05$
30.67	30.67	30.67	8	$35.84 \pm 0.18$	$29.95 \pm 0.12$	$25.52 \pm 0.03$	$8.68 \pm 0.32$

Table 2: Nominal and measured alloy compositions. Values are in at.% with absolute standard errors shown.

Eight alloys were fabricated as ingots weighing approximately 25 g using an arc melting process in an argon atmosphere. The ingots were inverted and remelted three times to ensure homogeneity. Sections of each ingot were cut off, wrapped in tantalum foil, and then encapsulated in a quartz ampoule backfilled with low pressure argon. These samples then underwent a homogenisation heat

1  
2  
3  
4  
5  
6  
7  
8  
9 treatment at 1200 °C for 100 hours, before quenching in water.

10 Secondary electron microscopy (SEM) specimens were prepared using stan-  
11 dard metallographic techniques. The final polish was performed with an 0.06  $\mu\text{m}$   
12 oxide polishing suspension. Back scattered electron (BSE) images were obtained  
13 using a Zeiss Ultra55 microscope at 10 kV. Transmission electron microscopy  
14 (TEM) foils were produced by electropolishing punched sections of thin foils  
15 in a 5% perchloric acid-methanol solution with a temperature of -40 °C using  
16 a Tenupol 5 twin jet electropolisher at a voltage of 29 V. A ThermoScientific  
17 Talos TEM with an accelerating voltage of 200 kV was used to produce annular  
18 dark field (ADF) images and energy dispersive X-ray (EDX) maps. Wavelength  
19 dispersive spectroscopy (WDS) was performed using a JEOL JXA-8530F FEG  
20 electron probe microanalyser (EPMA). Quantification was performed at 20 kV,  
21 10 nA for Ti  $K\alpha$ , V  $K\alpha$ , Cr  $K\alpha$  and Mn  $K\beta$  standardised against pure met-  
22 als. 100 composition measurements were randomly taken from an area 500  $\mu\text{m}$   
23 in radius for each sample. Overlap corrections were applied to the raw X-ray  
24 intensities where required (Ti  $K\beta$  on V  $K\alpha$ , V  $K\beta$  on Cr  $K\alpha$ ) and corrected iter-  
25 atively using the PAP phi-rho-Z matrix correction routine using NIST FFAST  
26 mass absorption coefficients. X-ray maps were conducted at 10 kV and 163 nA  
27 (V-40Cr-20Mn, Fig. 2) and 46 nA (V-Cr-Mn-8%Ti, Fig. 3). Vickers hardness  
28 measurements were taken with a load of 9.8 N and dwell time of 10 s using a  
29 Matsuzawa MMT-X indenter. Nine hardness measurements were made spaced  
30 0.5 mm apart in a three by three grid formation.  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43

44 WDS analysis suggests that there is a difference between the intended alloy  
45 composition and what is found in practice (see Table 2). In particular, the at.%  
46 of Mn is lower than expected in all alloys. This is likely to be caused by the low  
47 vapour pressure of Mn, leading to evaporation during the arc melting process.  
48  
49

50 BSE images (Fig. 1) of the alloys show a microstructure consisting of a light  
51 grey matrix with darker precipitates. The precipitates found in the ternary  
52 alloys (Fig. 1 (a) to (d)) are a mixture of larger, more rounded shapes which  
53 appear along grain boundaries, and smaller long and thin precipitates that are  
54 intragranular. The quaternary alloys have much finer precipitates (Fig. 1 (e) to  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

1  
2  
3  
4  
5  
6  
7  
8  
9 (h)). The matrix appeared as a single phase in all alloys. This was confirmed to  
10 be bcc ( $a = 2.90 - 3.04 \text{ \AA}$ ) through X-ray (see supplementary information) and  
11 TEM diffraction. These microstructures and lattice parameters are consistent  
12 with observations of a bcc Ti-V-Cr-Mn alloy with differing composition, used  
13 for hydrogen storage[24].  
14

15  
16 WDS was utilised to determine the composition of the matrix and precipitate  
17 phases. The matrix appeared to be a homogeneous mixture of the constituent  
18 metals in both the ternary (Fig. 2) and the quaternary alloys (Fig. 3). The  
19 main difference between the two types of alloy was in the composition of the  
20 precipitates. The ternary precipitates were depleted in Mn and Cr, and also con-  
21 tained large amounts of oxygen. No segregation of other interstitial impurities  
22 (namely carbon and nitrogen) was observed. However, the precipitates in the  
23 Ti-containing alloys were extremely Ti rich relative to the matrix and were also  
24 enriched in all three impurity elements studied. This suggests that the addition  
25 of Ti to these alloys acts as a getter for these interstitial impurities, forming  
26 Ti-[C,O,N] type precipitates similar to those found in V-4Cr-4Ti.[3, 18, 19]  
27  
28  
29  
30  
31  
32  
33

34 TEM was used to check for smaller scale elemental segregation as shown  
35 in Fig. 4. No segregation was found, indicating a homogeneous bcc phase  
36 across all lengthscales. Diffraction patterns of the precipitates could not be  
37 obtained owing to the electropolishing procedure preferentially removing the  
38 matrix, leaving precipitates that were too thick for diffraction.  
39  
40  
41

42 Hardness values were found to range from 348 to 456 HV in the homogenised  
43 state (see supplementary information). Hardness decreased slightly after ho-  
44 mogenisation for all alloys. The Ti containing alloys were all harder than  
45 their equiatomic ternary equivalent, V-Cr-Mn, which may indicate the solute  
46 strengthening caused by introducing Ti[22, 23] is the more dominant effect com-  
47 pared to the softening from gettering interstitial impurities[21]. A high ductile-  
48 to-brittle temperature and embrittlement by interstitial elements are foreseeable  
49 issues with these alloys, as they are with most refractory-based alloys. Hence, in  
50 order to assess their suitability for manufacture and service, larger-scale mechan-  
51 ical property and processibility investigations are needed alongside long-term  
52  
53  
54  
55  
56  
57  
58

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

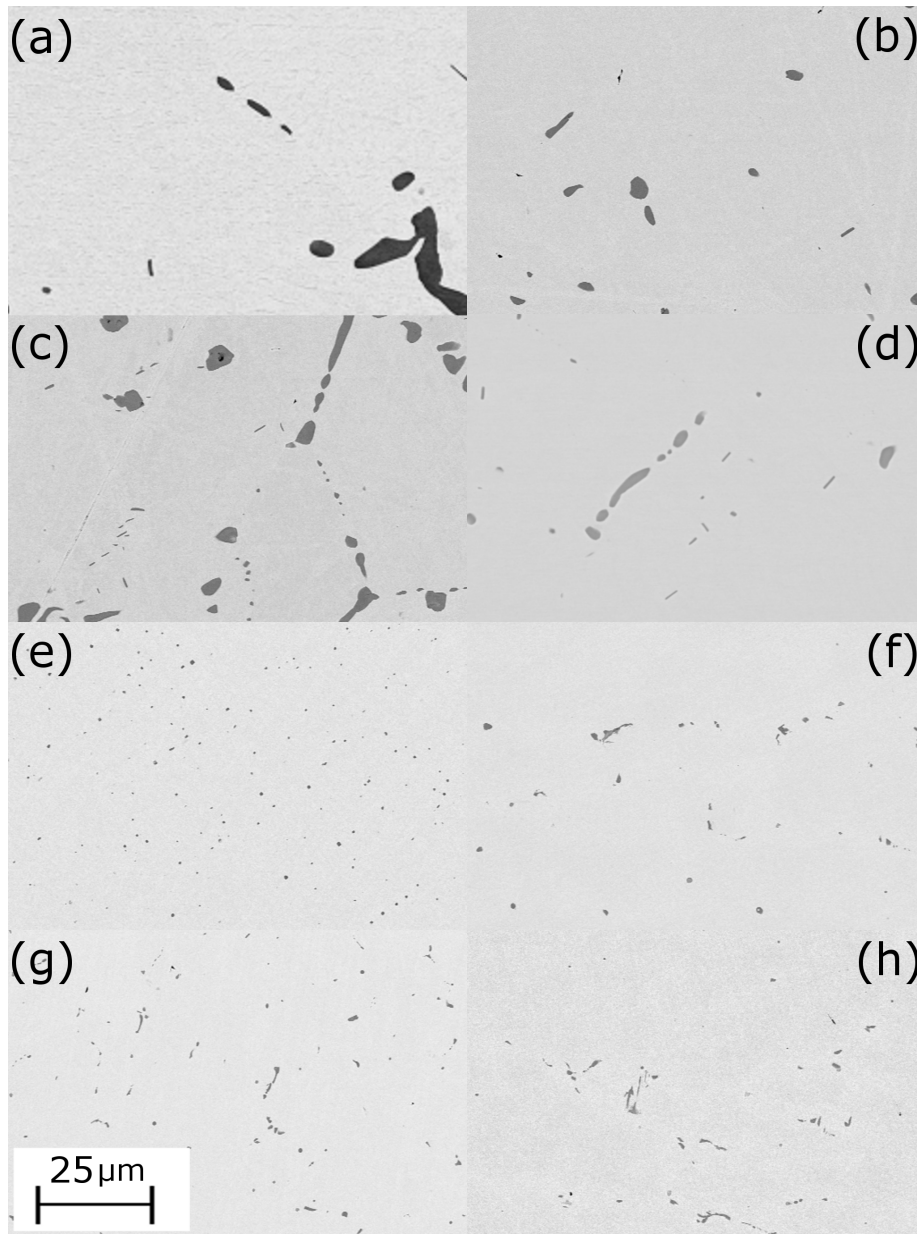


Figure 1: Representative BSE images of alloy (a) V-20Cr-20Mn (b) V-20Cr-40Mn (c) V-40Cr-20Mn (d) V-Cr-Mn (e) V-Cr-Mn-1%Ti (f) V-Cr-Mn-2%Ti (g) V-Cr-Mn-4%Ti (h) V-Cr-Mn-8%Ti

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

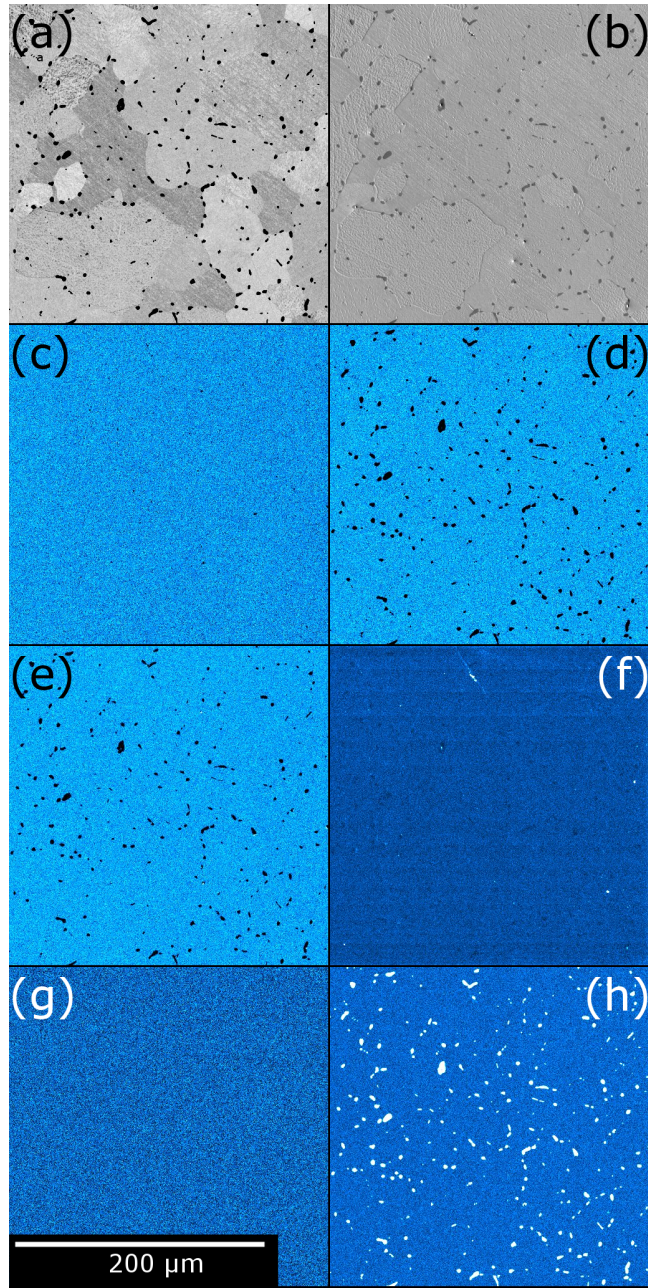


Figure 2: WDS map of alloy V-40Cr-20Mn showing: (a) BSE image (b) secondary electron image (c) V (d) Cr (e) Mn (f) C (g) N (h) O



1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

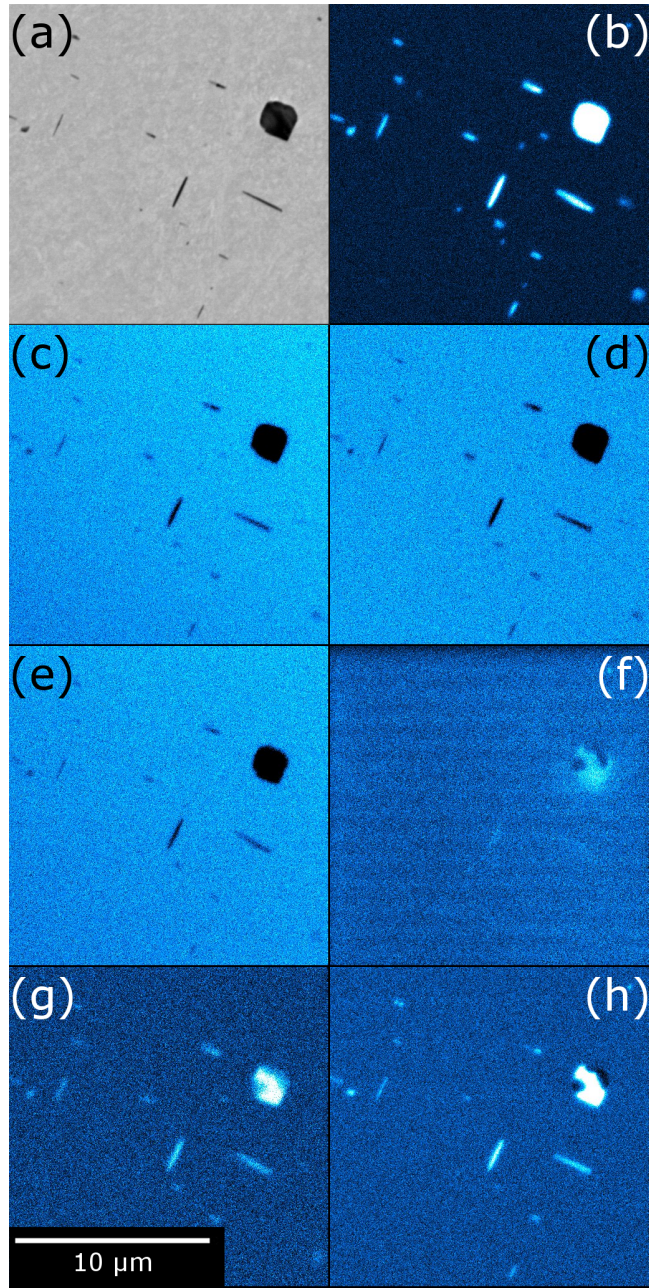


Figure 3: WDS map of alloy V-Cr-Mn-8%Ti showing: (a) BSE image (b) Ti (c) V (d) Cr (e) Mn (f) C (g) N (h) O

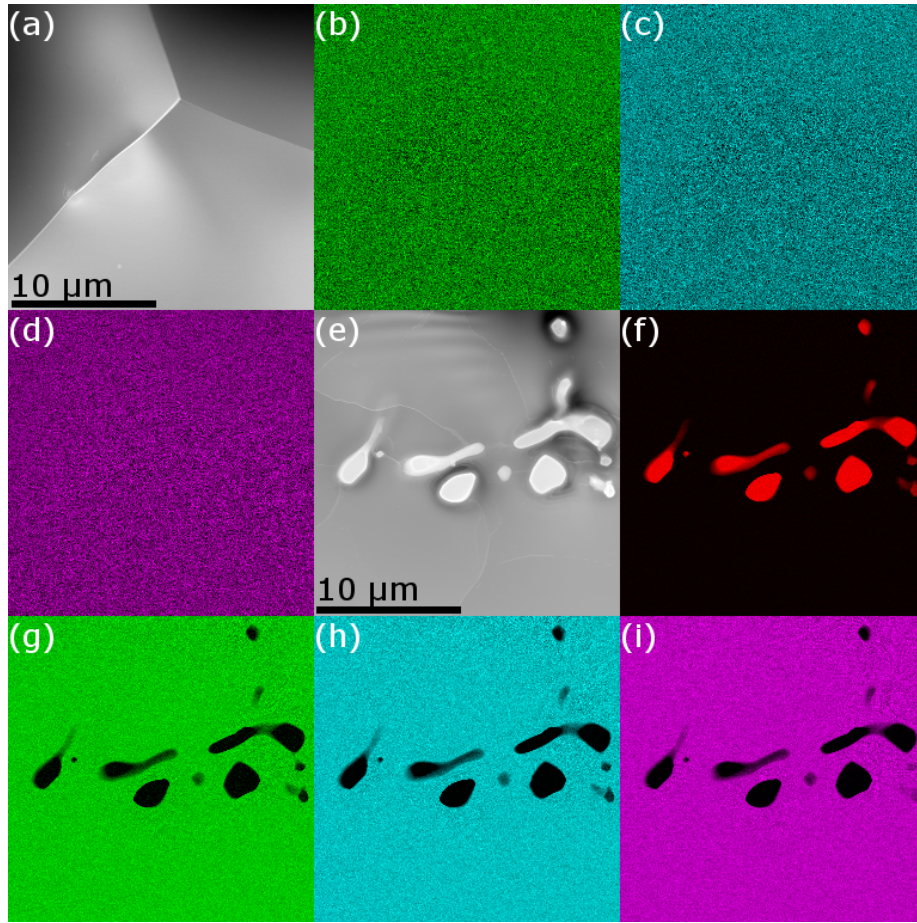


Figure 4: Alloy V-Cr-Mn: (a) ADF image (b) V map (c) Cr map (d) Mn map. Alloy V-Cr-Mn-4%Ti precipitate: (e) ADF image (f) Ti map (g) V map (h) Cr map (i) Mn map.

ageing experiments.

To summarise, this study has found that a suite of alloys fabricated from low-activation elements consists of a single bcc phase, with precipitates forming from interstitial impurity elements. The results are promising for the development of high-entropy alloys for use in fusion applications due to the observation of only a single metallic matrix phase after homogenisation. Such microstructures provide an excellent launchpad for the future development of specialist alloys for fusion applications.

1  
2  
3  
4  
5  
6  
7  
8  
9 **Acknowledgements**

10  
11 The authors acknowledge the use of the Department of Materials X-ray  
12 Diffraction Suite at the University of Manchester and for the technical support,  
13 advice and assistance provided by Dr. John E. Warren. The authors acknowl-  
14 edge funding from the EPSRC Centre for Doctoral Training in Fusion Energy  
15 (grant EP/L01663X/1) as well as EPSRC grant EP/R021546/1.  
16  
17  
18  
19

- 20 [1] A. Raffray, M. Akiba, V. Chuyanov, L. Giancarli, S. Malang,  
21 Journal of Nuclear Materials 307-311 (2002) 21–30. URL: [https://](https://linkinghub.elsevier.com/retrieve/pii/S0022311502011741)  
22 [linkinghub.elsevier.com/retrieve/pii/S0022311502011741](https://linkinghub.elsevier.com/retrieve/pii/S0022311502011741). doi:10.  
23 1016/S0022-3115(02)01174-1.  
24  
25  
26  
27 [2] M. Gilbert, T. Eade, C. Bachmann, U. Fischer, N. Taylor, Nuclear Fusion  
28 57 (2017) 046015. URL: [http://stacks.iop.org/0029-5515/57/i=4/](http://stacks.iop.org/0029-5515/57/i=4/a=046015?key=crossref.544c7e45254fdd697aa0a979a75bc8a4)  
29 [a=046015?key=crossref.544c7e45254fdd697aa0a979a75bc8a4](http://stacks.iop.org/0029-5515/57/i=4/a=046015?key=crossref.544c7e45254fdd697aa0a979a75bc8a4). doi:10.  
30 1088/1741-4326/aa5bd7.  
31  
32  
33  
34 [3] T. Muroga, J. Chen, V. Chernov, R. Kurtz, M. Le Flem, Journal of Nuclear  
35 Materials 455 (2014) 263–268. doi:10.1016/j.jnucmat.2014.06.025.  
36  
37  
38 [4] S. Zinkle, J.-L. Boutard, D. Hoelzer, A. Kimura, R. Lindau, G. Odette,  
39 M. Rieth, L. Tan, H. Tanigawa, Nuclear Fusion 57 (2017) 092005.  
40 URL: [http://iopscience.iop.org/0029-5515/57/9/092005http:](http://iopscience.iop.org/0029-5515/57/9/092005http://stacks.iop.org/0029-5515/57/i=9/a=092005?key=crossref.7eee51a66e6efe91bcfe2b369ccd79df)  
41 [//stacks.iop.org/0029-5515/57/i=9/a=092005?key=crossref.](http://iopscience.iop.org/0029-5515/57/9/092005http://stacks.iop.org/0029-5515/57/i=9/a=092005?key=crossref.7eee51a66e6efe91bcfe2b369ccd79df)  
42 [7eee51a66e6efe91bcfe2b369ccd79df](http://iopscience.iop.org/0029-5515/57/9/092005http://stacks.iop.org/0029-5515/57/i=9/a=092005?key=crossref.7eee51a66e6efe91bcfe2b369ccd79df). doi:10.1088/1741-4326/57/9/  
43 092005.  
44  
45  
46  
47  
48 [5] A. Rowcliffe, L. Garrison, Y. Yamamoto, L. Tan, Y. Ka-  
49 toh, Fusion Engineering and Design 135 (2018) 290–301. URL:  
50 [http://dx.doi.org/10.1016/j.fusengdes.2017.07.012https:](http://dx.doi.org/10.1016/j.fusengdes.2017.07.012https://linkinghub.elsevier.com/retrieve/pii/S0920379617307524)  
51 [//linkinghub.elsevier.com/retrieve/pii/S0920379617307524](http://dx.doi.org/10.1016/j.fusengdes.2017.07.012https://linkinghub.elsevier.com/retrieve/pii/S0920379617307524).  
52 doi:10.1016/j.fusengdes.2017.07.012.  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

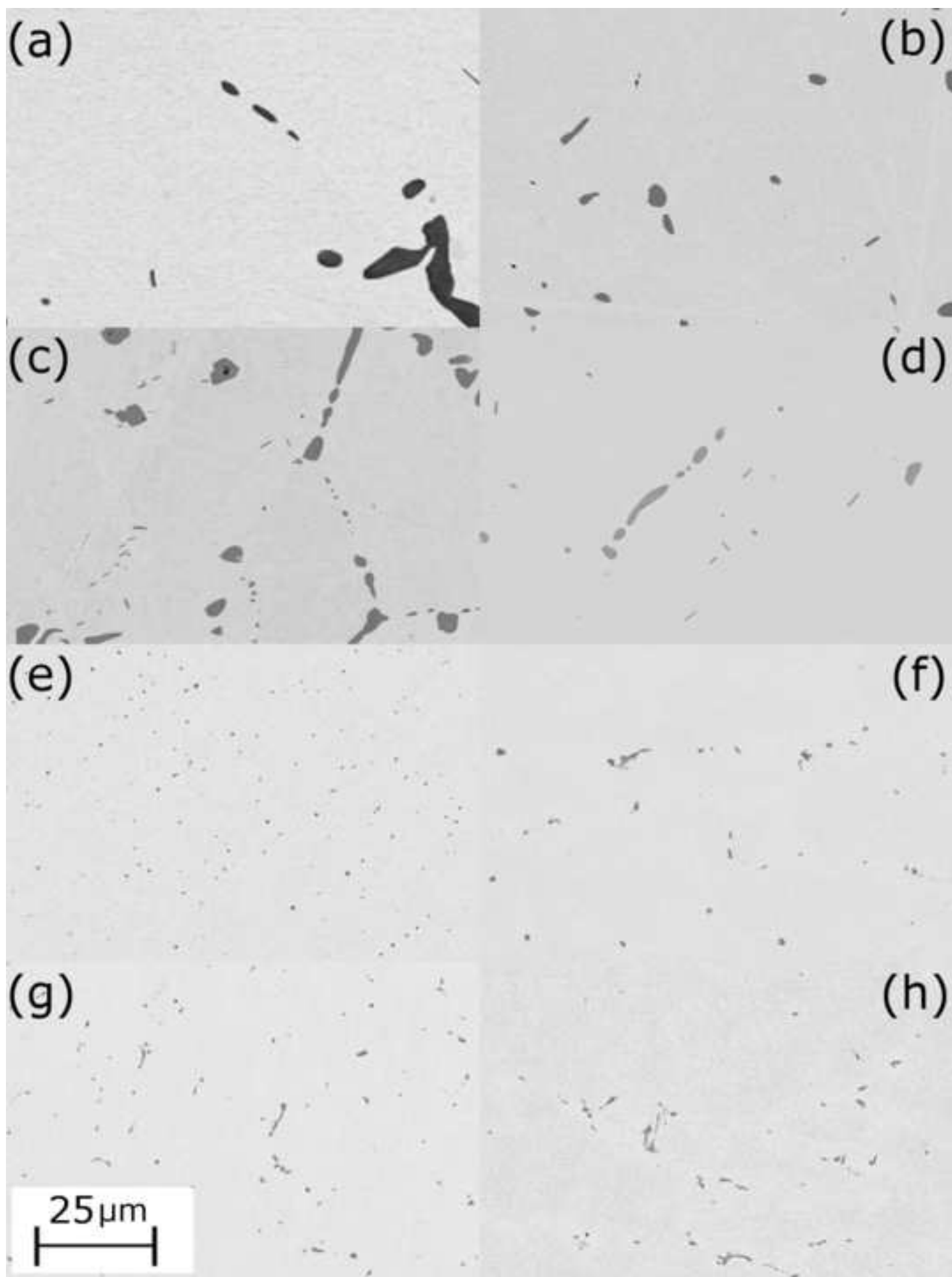
- 1  
2  
3  
4  
5  
6  
7  
8  
9 [6] S. J. Zinkle, N. M. Ghoniem, *Fusion Engineering and Design* 51-52 (2000)  
10 55–71. doi:10.1016/S0920-3796(00)00320-3.  
11  
12 [7] A. Ayyagari, R. Salloom, S. Muskeri, S. Mukherjee, *Materialia* 4 (2018)  
13 99–103. URL: [https://www.sciencedirect.com/science/article/pii/](https://www.sciencedirect.com/science/article/pii/S2589152918301261)  
14 [S2589152918301261](https://www.sciencedirect.com/science/article/pii/S2589152918301261). doi:10.1016/J.MTLA.2018.09.014.  
15  
16 [8] B. Gludovatz, A. Hohenwarter, D. Catoor, E. H. Chang, E. P.  
17 George, R. O. Ritchie, *Science* 345 (2014) 1153–1158. URL:  
18 <http://science.sciencemag.org/content/sci/345/6201/1153.full>.  
19 [pdf](http://science.sciencemag.org/content/sci/345/6201/1153.full.pdf)<http://www.sciencemag.org/cgi/doi/10.1126/science.1254581>.  
20 doi:10.1126/science.1254581.  
21  
22 [9] K. Jin, C. Lu, L. Wang, J. Qu, W. Weber, Y. Zhang,  
23 H. Bei, *Scripta Materialia* 119 (2016) 65–70. URL: [https://](https://linkinghub.elsevier.com/retrieve/pii/S1359646216301154)  
24 [linkinghub.elsevier.com/retrieve/pii/S1359646216301154](https://linkinghub.elsevier.com/retrieve/pii/S1359646216301154).  
25 doi:10.1016/j.scriptamat.2016.03.030.  
26  
27 [10] O. Carlson, A. Eustice, *Ames Laboratory Technical Reports* (1959). URL:  
28 [http://lib.dr.iastate.edu/ameslab\\_{\\_}isreports/12](http://lib.dr.iastate.edu/ameslab/_isreports/12).  
29  
30 [11] F. Garner, M. Toloczko, B. Sencer, *Journal of Nuclear Materials* 276  
31 (2000) 123–142. URL: [https://www.sciencedirect.com/science/](https://www.sciencedirect.com/science/article/pii/S0022311599002251)  
32 [article/pii/S0022311599002251](https://www.sciencedirect.com/science/article/pii/S0022311599002251)[https://linkinghub.elsevier.](https://linkinghub.elsevier.com/retrieve/pii/S0022311599002251)  
33 [com/retrieve/pii/S0022311599002251](https://linkinghub.elsevier.com/retrieve/pii/S0022311599002251). doi:10.1016/S0022-3115(99)  
34 00225-1.  
35  
36 [12] S. Zinkle, *Comprehensive Nuclear Materials* (2012) 65–98.  
37 URL: [https://www.sciencedirect.com/science/article/pii/](https://www.sciencedirect.com/science/article/pii/B9780080560335000033)  
38 [B9780080560335000033](https://www.sciencedirect.com/science/article/pii/B9780080560335000033). doi:10.1016/B978-0-08-056033-5.00003-3.  
39  
40 [13] S. Zinkle, L. Snead, *Annual Review of Materials Research*  
41 44 (2014) 241–267. URL: [www.annualreviews.org](http://www.annualreviews.org)[http://www.](http://www.annualreviews.org/doi/10.1146/annurev-matsci-070813-113627)  
42 [annualreviews.org/doi/10.1146/annurev-matsci-070813-113627](http://www.annualreviews.org/doi/10.1146/annurev-matsci-070813-113627).  
43 doi:10.1146/annurev-matsci-070813-113627.  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

- 1  
2  
3  
4  
5  
6  
7  
8  
9 [14] T. Massalski, Binary alloy phase diagrams, ASM International, 1986.  
10  
11 [15] A. Klopotov, I. Kurzina, A. Potekaev, A. Ustinov, T. Dement, L. Kazantseva,  
12 E. Marchenko, N. Karakchieva, MATEC Web of Conferences  
13 243 (2018) 00014. URL: <https://www.matec-conferences.org/10.1051/matecconf/201824300014>. doi:10.1051/matecconf/201824300014.  
14  
15  
16  
17  
18 [16] E. J. Pickering, N. G. Jones, International Materials Reviews 6608 (2016) 1–  
19 20. URL: <http://www.tandfonline.com/doi/full/10.1080/09506608.2016.1180020>. doi:10.1080/09506608.2016.1180020.  
20  
21  
22  
23 [17] D. Miracle, O. Senkov, Acta Materialia 122 (2017) 448–511.  
24 URL: <https://www.sciencedirect.com/science/article/pii/S1359645416306759>  
25 <https://linkinghub.elsevier.com/retrieve/pii/S1359645416306759>. doi:10.1016/j.actamat.2016.08.081.  
26  
27  
28  
29  
30 [18] D. Hoelzer, Structural analysis of Ti-oxycarbonitrides in V-Cr-Ti based  
31 alloys, Technical Report, Oak Ridge National Laboratory, 1999.  
32  
33  
34 [19] T. Nagasaka, N. Heo, T. Muroga, M. Imamura, Fusion Engineering and Design 61-62 (2002) 757–762. URL: <https://www.sciencedirect.com/science/article/pii/S0920379602002582>  
35 <https://linkinghub.elsevier.com/retrieve/pii/S0920379602002582>.  
36  
37  
38  
39  
40  
41  
42  
43  
44 [20] S. Hoile, Materials Science and Technology 16 (2000) 1079–1093.  
45 URL: <https://www.tandfonline.com/action/journalInformation?journalCode=ymst20>  
46 <http://www.tandfonline.com/doi/full/10.1179/026708300101506902>. doi:10.1179/026708300101506902.  
47  
48  
49  
50 [21] J. M. Chen, V. M. Chernov, R. J. Kurtz, T. Muroga, Journal of Nuclear  
51 Materials 417 (2011) 289–294. URL: <http://dx.doi.org/10.1016/j.jnucmat.2011.02.015>. doi:10.1016/j.jnucmat.2011.02.015.  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

- 1  
2  
3  
4  
5  
6  
7  
8  
9 [22] B. Loomis, H. Chung, L. Nowicki, D. Smith, *Journal of Nuclear Mate-*  
10 *rials* 212-215 (1994) 799–803. URL: [http://linkinghub.elsevier.com/](http://linkinghub.elsevier.com/retrieve/pii/002231159490166X)  
11 [retrieve/pii/002231159490166X](http://linkinghub.elsevier.com/retrieve/pii/002231159490166X). doi:10.1016/0022-3115(94)90166-X.  
12  
13  
14 [23] H. M. Chung, B. A. Loomis, D. L. Smith, *Journal of Nuclear Materials* 239  
15 (1996) 139–156. doi:10.1016/S0022-3115(96)00676-9.  
16  
17  
18 [24] T. Fuda, A. Kamegawa, Y. Tominaga, T. Kuriwa, K. Matsumoto,  
19 T. Tamura, H. Takamura, M. Okada, *Journal of Alloys and Compounds*  
20 330-332 (2002) 522–525. URL: [www.elsevier.com/locate/jallcomhttp:](http://www.elsevier.com/locate/jallcomhttp://linkinghub.elsevier.com/retrieve/pii/S0925838801015444)  
21 [//linkinghub.elsevier.com/retrieve/pii/S0925838801015444](http://linkinghub.elsevier.com/retrieve/pii/S0925838801015444).  
22 doi:10.1016/s0925-8388(01)01544-4.  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

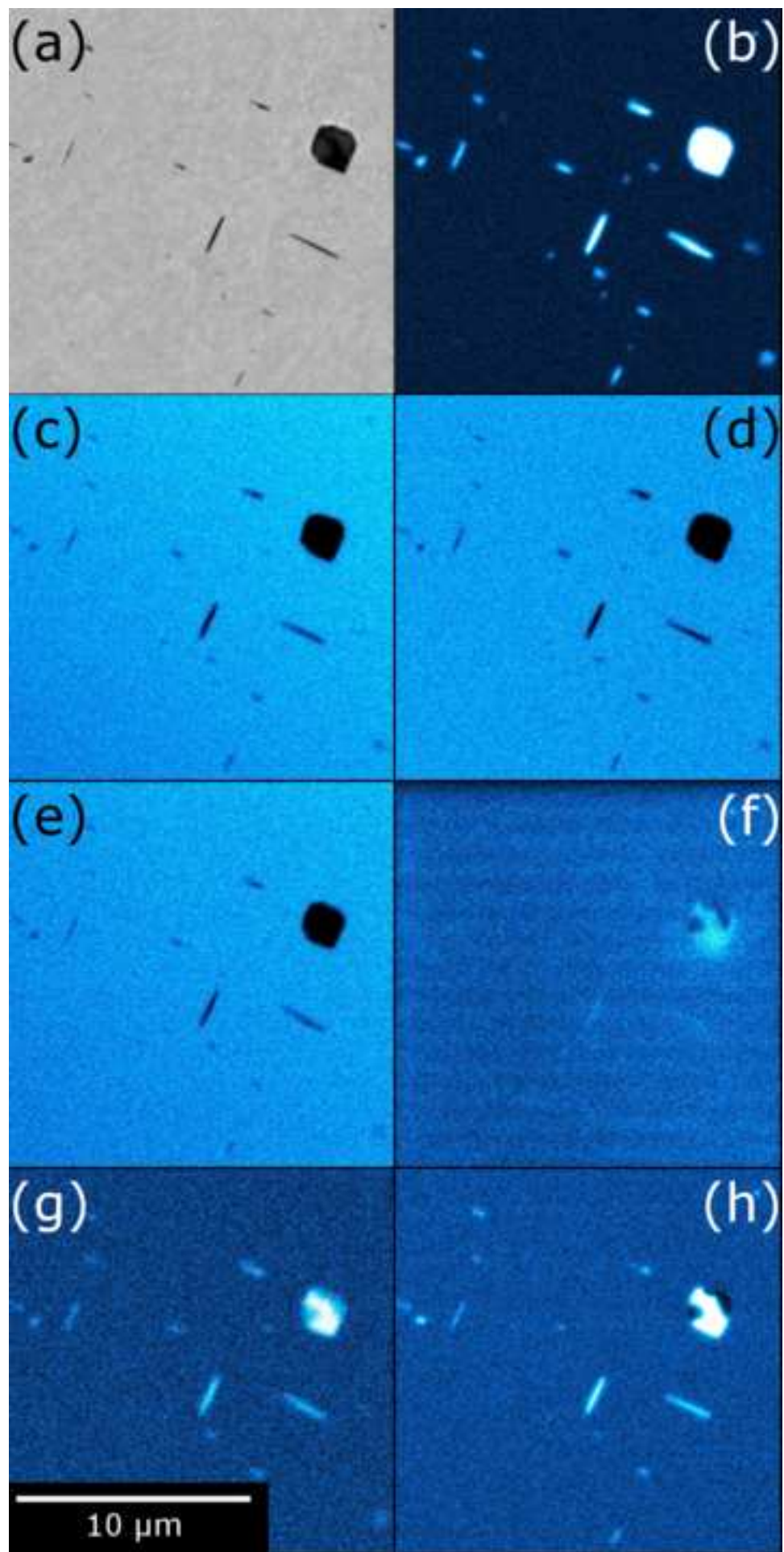
**LaTeX Source Files**

[Click here to download LaTeX Source Files: scripta\\_formatted.zip](#)



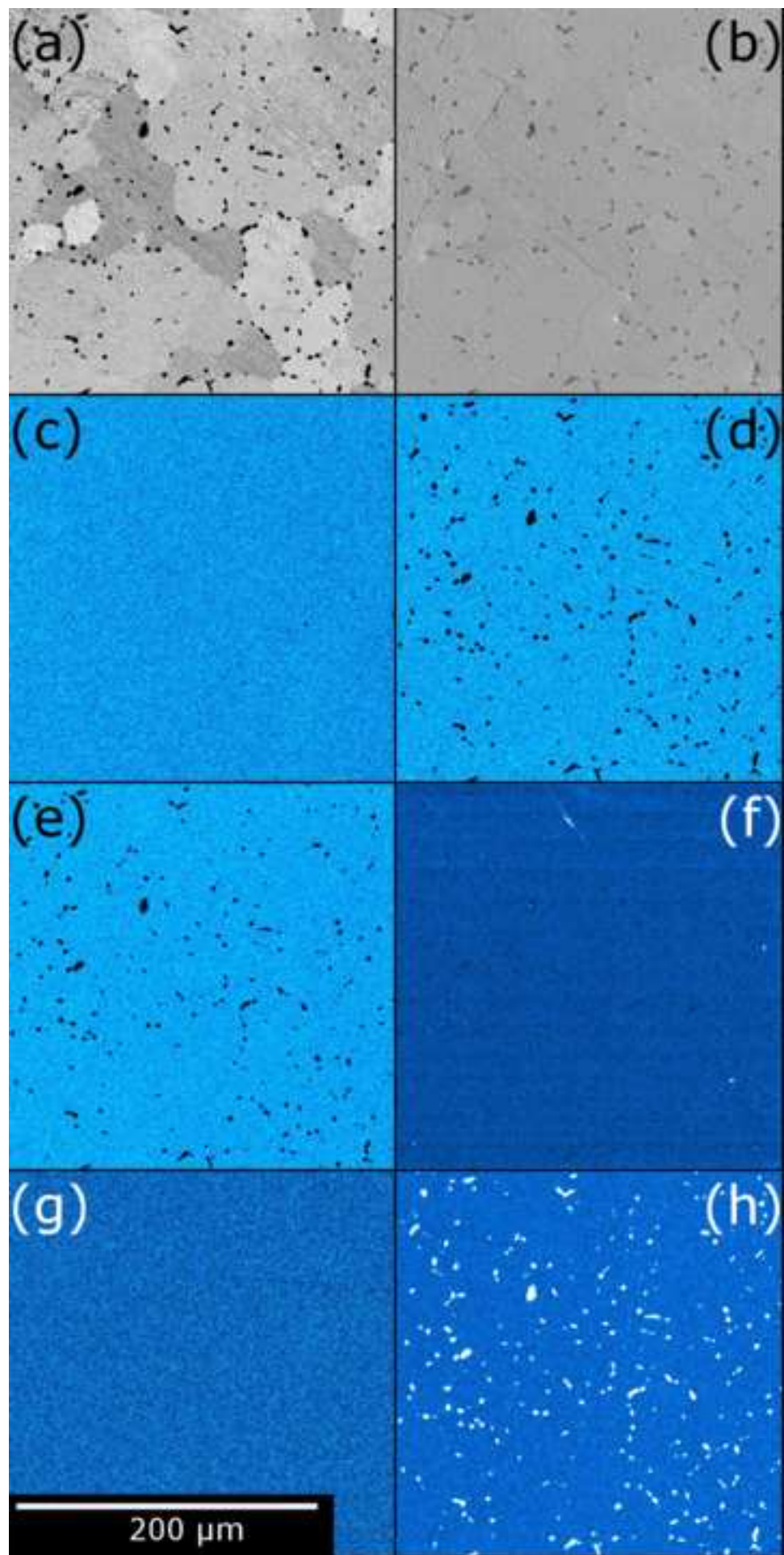


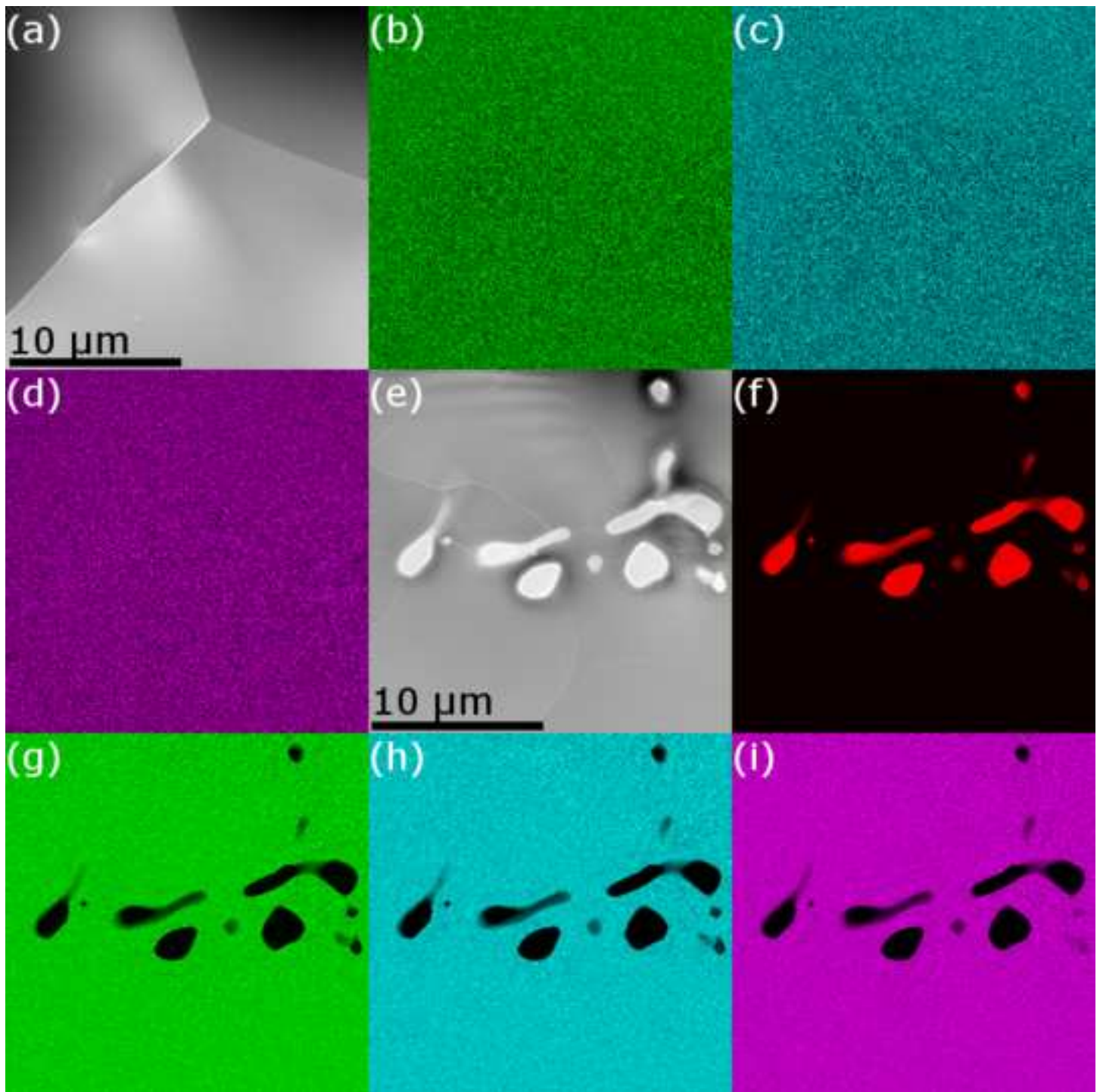
Figure(s)  
[Click here to download high resolution image](#)



Figure(s)

[Click here to download high resolution image](#)





**Supplementary Material**

[Click here to download Supplementary Material: Supplementary\\_figures.pdf](#)