**A review of the irradiation evolution of dispersed oxide nanoparticles in the b.c.c.
Fe-Cr system: current understanding and future directions**

Janelle P. Wharry^{1*}, Matthew J. Swenson², Kayla H. Yano²

¹Purdue University, 400 Central Drive, West Lafayette, IN 47907, USA

²Boise State University, 1910 University Drive, Boise, ID 83725, USA

*Corresponding Author

Name: Janelle P. Wharry

Postal Address: 400 Central Drive, West Lafayette, Indiana, USA

Telephone Number: +1 765 494 0782

E-mail address: jwharry@purdue.edu

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¹Purdue University, 400 Central Drive, West Lafayette, IN 47907, USA

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Abstract

Thus far, a number of studies have investigated the irradiation evolution of oxide nanoparticles in b.c.c. Fe-Cr based oxide dispersion strengthened (ODS) alloys. But given the inconsistent experimental conditions, results have been widely variable and inconclusive. Crystal structure and chemistry changes differ from experiment to experiment, and the total nanoparticle volume fraction has been observed to both increase and decrease. Furthermore, there has not yet been a comprehensive review of the archival literature. In this paper, we summarize the existing studies on nanoparticle irradiation evolution. We note significant observations with respect to oxide nanoparticle crystallinity, composition, size, and number density. We discuss three possible contributing mechanisms for nanoparticle evolution: ballistic dissolution, Ostwald ripening, and irradiation-enhanced diffusion. Finally, we propose future directions to achieve a more comprehensive understanding of irradiation effects on oxide nanoparticles in ODS alloys.

Keywords: oxide dispersion strengthened, Ostwald ripening, ballistic dissolution

1. Introduction

The objective of this paper is to provide a critical review of the state-of-the-research on the irradiation evolution of oxide nanoparticles in body centered cubic (b.c.c.) Fe-Cr based oxide dispersion strengthened (ODS) alloys. ODS alloys are candidate materials for fusion and advanced fission reactor concepts [1], [2]. Specifically, they are proposed for use as fusion first wall and blanket materials, as well as for fuel cladding, duct, and structural components for advanced gas reactor and liquid metal fast reactor concepts. In such proposed settings, ODS alloys will be subject to temperatures in the range 500-700°C and irradiation fluences on the order of several hundred displacements per atom (dpa) [1], [2].

ODS have gained interest as candidate materials for these extreme applications for several reasons. First, they exhibit excellent high-temperature strength and creep resistance [3]–[6]. Second, they are low activation. And finally, their fine dispersion of oxide nanoparticles (NPs) is believed to provide resistance to irradiation damage, specifically void swelling and bubble growth [3]–[6]. However, many studies have observed irradiation-induced changes to NP size, number density, chemistry, and/or crystal structure. Any changes in NPs will have implications on mechanical properties, irradiation defect cluster evolution, and material performance, especially at high irradiation damage levels [3], [4]. Thus, understanding the irradiation evolution of NPs is key to our ability to predict long-term material degradation, and is thus a critical knowledge gap that must be addressed.

Unfortunately, the studies of irradiation evolution of NPs remain inconclusive for several reasons. Most critically, the studies have all been conducted using different ODS alloys that have been fabricated, processed, or heat treated differently (common alloy nominal compositions are provided in Table 1); they have used different irradiation conditions such as particle type and energy, dose, dose rate, and temperature; and they have differing initial NP compositions and morphologies. This large number of variable experimental parameters makes it impossible to compare results from one study to the next. Furthermore, no prior study has surveyed the entire body of literature on this topic, leading to conclusions that are inconsistent with results from un-cited references. Finally, studies have generally centered around the desire for “irradiation stability” of oxide NPs. Yet, every study defines stability differently, with some studies focusing solely on crystal structure or chemistry, and others focusing on size and/or number density.

2. Summary of existing results

All studies on irradiation evolution of ODS NPs, to the best of the authors’ knowledge, are summarized in Table 2. It is clear that all possible irradiation-induced changes to NPs have been observed: from crystalline stability to amorphization, from growth and coarsening to dissolution, and a variety of chemistry changes. There are no clear trends with respect to experimental parameters, either. However, it is evident that crystal structure, chemistry, and volume fraction (i.e. the combination of size and number density) are all important parameters to defining the irradiation evolution of oxide NPs.

Henceforth, we refer to “irradiation evolution” rather than “irradiation stability”, and examine all three of these factors.

2.1 Size, number density, and volume fraction

Size changes are the most widely reported factor describing the irradiation evolution of NPs, and it is of interest to understand these size changes as a function of irradiation dose. Only a few studies have carried out NP size measurements over a range of doses (with all other irradiation parameters fixed); these results are represented in Figure 1. But this figure does not lend much understanding to the dose evolution of NP size. Rather, it illustrates the inconsistency of NP irradiation evolution, underscoring the need for this manuscript: within the contextual envelope of a single paper, one can make sense of one’s results; but when placed in the context of all other studies (on different alloys, at different temperatures, with different irradiating particles, using different analytical techniques), the picture becomes muddy. For example, Allen, *et al.* [7] and Chen, *et al.* [8] both observe decreasing NP size with increasing dose, with a steady-state reached between 50 and 150 dpa. But the similarities end there. The two studies report contradictory temperature functionality: Chen, *et al.* [8] report the most significant NP size decreases <500°C, whereas Allen, *et al.* [7] report the most significant NP size decreases >500°C. Further clouding the picture is the fact that there are reports of NP coarsening with increasing dose [9], [10], and reports of NPs exhibiting little to no size change with increasing dose [11], [12]. The data presented in Figure 1 illustrate that

results from inconsistent experiment conditions are impossible to interpret in a broad context. The same can be said for NP number density as a function of irradiation dose.

Since plots of size or number density as a function of irradiation dose are relatively ineffective, we instead plot results from the archival literature on axes of irradiation temperature vs. dose (Figure 2). The irradiation-induced direction of change in NP size (Figure 2a) or NP number density (Figure 2b) is indicated as a green triangle for increase, red diamond for decrease, or grey circle for no change (i.e. stability). These figures demonstrate that there is no clear correlation between irradiation dose, irradiation temperature, and the direction of change in NP size or number density.

Size and number density have generally been considered separately, but recently it has been advocated to report them collectively as a volume fraction [7], [13]–[15]. For example, in 9Cr ODS irradiated with Ni^+ ions, Allen, *et al.* [7] observe oxides to decrease in size, but increase in number density. This yielded a net result of stable or, in some cases, decreasing volume fraction. Swenson [15] shows that volume fraction is key to correlating irradiation-induced microstructural changes to the changes in yield strength. It is also illustrative to plot the direction of change in volume fraction on the irradiation temperature-dose axes (Figure 2c). This plot shows that studies observing decreases in NP volume fraction were generally conducted at irradiation temperatures $>600^\circ\text{C}$, while studies with stable or increasing NP volume fraction were conducted at irradiation temperatures $<600^\circ\text{C}$. However, with so few data points available (i.e. not all studies have reported volume fraction), one cannot conclude with certainty that the NP volume fraction is correlated with irradiation temperature.

Another phenomena that complicates the reporting of post-irradiation NP size and number density is the “halo” effect, in which irradiation induces the formation of multiple smaller NPs around the periphery of a larger NP [16], [17]. Haloing can alter the NP size and number density, but it does not significantly alter the total NP volume fraction. Thus, when characterizing irradiation evolution of NPs, one should consider volume fraction in addition to reporting just size and number density.

When using APT to evaluate both NP size and chemistry, it is crucial that researchers report the chemical composition of both the matrix and NPs under irradiation. For example, an irradiation-induced decrease in NP size measured by APT could errantly be attributed to evolving NP chemistry. However, in the case of neutron-irradiated 9Cr ODS, a decrease in NP size is confirmed by simultaneously observing stable Y, Ti, and O concentrations in the NPs, with an increase in Y, Ti, and O concentrations in the matrix [14]. This illustrates the importance of holistically studying the NP structure, composition, and volume fraction to fully understand their irradiation evolution.

2.2 Chemistry

Historically, NP chemistry has been studied by transmission electron microscopy (TEM) using the electron energy loss spectroscopy (EELS) or energy filtered TEM (EFTEM) techniques. However, the recent application of atom probe tomography (APT) to oxide NP analysis has enabled higher-resolution tracking of NP composition. Yet, most APT techniques detect only 36-50% of all atoms in the specimen, so the exact stoichiometry remains difficult to detect with reasonable certainty. Thus, most work focuses on relative irradiation-induced changes to NP composition.

It is convenient to discuss irradiation-induced compositional changes to NPs in terms of the Y:Ti ratio and (Y+Ti):O ratio. The prior has been observed to both increase [9], [14]–[16], [18]–[23] and decrease [23]–[28] with irradiation. Yet, the (Y+Ti):O ratio remains generally stable [14], [15], [18], [19], [23]. It is suggested that composition changes, specifically the increase in Y:Ti ratio, drive the NPs toward $\text{Y}_2\text{Ti}_2\text{O}_7$ stoichiometry [9]. Additional chemical changes induced by irradiation and observed by several researchers include Cr enrichment at NPs [29], [30], and loss or depletion of Al from NPs [16], [20]. The Cr enrichment is attributed to radiation-induced segregation (RIS) of Cr to defect sinks such as NPs [30]–[32].

It is informative to plot the direction of change in Y:Ti and (Y+Ti):O ratios on the irradiation temperature-dose axes (Figure 3a-b). Studies that have observed a decrease in the Y:Ti ratio tend to have irradiation temperatures $>500^\circ\text{C}$, while studies that have observed stable or increasing Y:Ti ratio tend to have irradiation temperatures $<500^\circ\text{C}$ (Figure 3a). It has been established that Y has a higher bond strength in Y_2O_3 than does Ti in TiO_2 [33], leading to Y [17], [34] having a higher displacement energy than Ti [28] in the Y-Ti-O NP. It thus follows that Y loss from NPs would occur only at higher irradiation temperatures, which could contribute to the observation of Y:Ti ratio decrease predominantly under high-temperature irradiation. Looking next at the (Y+Ti):O ratio (Figure 3b), there is no apparent correlation between irradiation temperature and the direction of change of the (Y+Ti):O ratio. However, it appears that the (Y+Ti):O ratio is stable at doses <50 dpa, while the ratio tends to change (either increases or decreases) at doses ~ 100 -150 dpa. But with so few data points are available, one cannot conclude with certainty that the (Y+Ti):O ratio is correlated with irradiation dose.

2.3 Crystal structure

Coherency with the matrix is believed to be a key parameter governing the role of oxide NPs as sinks for irradiation defects, and therefore a key parameter governing irradiation evolution of the NP [35]–[38]. High resolution transmission electron microscopy (HRTEM) have found oxide NPs to be generally coherent with the matrix, as characterized by a sharp, flat, and non-diffuse oxide/matrix interface [8], [10], [16], [39], [40]. In some cases, irradiation causes the oxide/matrix interface to become irregular [16], [39], [40] and less coherent [8].

At high irradiation temperatures, Skuratov, *et al.* [41] observed regions at the oxide/matrix interface dissolve into the matrix, thereby enhancing erosion of particle shape and encouraging their reduction in size. Similarly, Rogozhkin, *et al.* [21] have observed that irradiated NPs take a faceted form with a diffuse (i.e. not sharp) oxide/matrix interface, suggesting that amorphization first occurs at interfaces, leading to eventual dissolution of larger NPs (>10 nm initial diameter). Menut, *et al.* [35] and Chen, *et al.* [8] attribute the importance of the oxide/matrix interface structure to differences in interfacial energy associated with NPs of varying coherency.

In some studies, oxide NPs are observed to amorphize under irradiation, but not necessarily decrease in size or number density [9], [20], [35], [42]–[47]. In some cases, irradiation-amorphized NPs coexist with NPs that remain crystalline [8]. The extent of amorphization of oxide NPs is believed to be dependent primarily on three parameters: the nature of the oxide, the irradiation dose, and the irradiation temperature [43], [47]. Of these factors, temperature is most well-understood, and a critical amorphization

temperature can be determined for any given ODS system and irradiation conditions [43]. The effects of irradiation dose and the nature of the oxide are less well-understood [47]. However, amorphization attributed to electronic energy loss does not depend on the nature of the NPs – both spinels and pyrochlores amorphize [43]. On the other hand, ballistic damage (i.e. nuclear stopping) has been observed to induce amorphization in pyrochlores, but not in spinels [43].

3. Proposed mechanisms

A number of explanations have been offered to explain irradiation-induced changes in chemistry, size, and number density of NPs. Many of these explanations revolve around four major themes, or some combination thereof: ballistic dissolution from nuclear displacements, Ostwald ripening, irradiation-enhanced diffusion, and homogeneous nucleation. Each of these will be discussed further.

3.1 Ballistic dissolution

Ballistic dissolution describes the ejection of atoms from NPs – and the resultant shrinkage of NPs – due to ballistic collisions from irradiation damage cascades [39], [48]–[53]. Ballistic dissolution should consider two mechanisms: recoil dissolution, and disordering dissolution. Recoil dissolution is the displacement of a knock-on atom to a position outside of the NP. An interfacial atom must be ejected more than one nearest-neighbor distance so as to separate itself from the NP. Accumulation of recoil dissolution results in loss of atoms, and thus reduction in size, of the NP. Disordering dissolution

refers to the irradiation damage cascade-induced localized disordering of the NP. Atoms in the disordered region, then, are no longer part of the crystalline NP, and thus represent a reduction in size of the NP. Once displaced from the NP, species can back diffuse to the original NP, diffuse to another NP, diffuse into the matrix, or make ballistic jumps to another NP [38], [39].

The effects of ballistic dissolution can be isolated from thermal effects by conducting low temperature irradiations. Certain, *et al.* [11] conducted ion irradiations at -75°C , and observed that atoms ballistically ejected from NPs were frozen in the matrix with limited mobility, resulting in significant dissolution of NPs. The favorable binding of vacancy cluster-Cr-O complex defects [54] further supports the tendency for ballistically-ejected species to remain in solution (rather than reforming into clusters) at lower temperatures. Yet, there are also numerous observations of recoil resolution of oxide NPs at irradiation temperatures in excess of 400°C [8], [14]–[18], [20], [27], [29], [32], [35], [41], [44], [55], suggesting that temperature may not be the only factor determining whether atoms remain in solution.

Ballistic dissolution of larger NPs is the basis of two possible explanations for haloing [16], [17]. First, if the local composition of ejected solutes exceeds that required for homogeneous nucleation under irradiation, ejected solutes will nucleate into smaller oxides around the original, larger oxide. Second, since solubility increases under irradiation, ejected elements may be in solution during irradiation. Then upon conclusion of the irradiation, solubility decreases, causing recoiled elements to precipitate. Dubuisson, *et al.* [16] suggest that the haloing process could continue until the original oxide is completely dissolved.

3.2 Ostwald ripening

Ostwald ripening in solid solutions explains the dissolution of small NPs and their subsequent redeposition onto larger NPs (or adsorption by larger NPs), resulting in coarsening of larger NPs. The Ostwald ripening mechanism is driven by the fact that smaller particles are less stable than larger ones, owing to the higher interfacial solubility. This phenomenon provides the thermodynamic impetus to minimize surface area and surface tension (i.e. interfacial energy) between the NPs and matrix. Quantitatively, Ostwald ripening can be represented by the Gibbs-Thomson equation (or the Ostwald-Freundlich equation; these equation names are frequently used interchangeably in the literature). Given that the driving force of Ostwald ripening is the oxide/matrix interfacial energy, it is critical that one distinguish that Ostwald ripening occurs only for incoherent NPs [8].

Studies that have observed dissolution of smaller NPs and coarsening of larger NPs [21], [22] are consistent with the Ostwald ripening mechanism. It is suggested that Ostwald ripening-driven NP kinetics should scale as $\phi^{1/3}$, where ϕ is irradiation flux [9], [10]. Studies that have observed coarsening of NPs, in general, are often interpreted as consistent with the Ostwald ripening mechanism (e.g. ref [9]), but without the simultaneous dissolution of smaller NPs, it is unclear whether such observations can indeed be attributed to Ostwald ripening. It should also be noted that studies observing haloing [16], [17] or shrinkage of larger NPs [35] represent trends contrary to that suggested by Ostwald ripening, but consistent with inverse Ostwald ripening (see Section 3.5).

Molecular dynamics (MD) simulations of irradiation damage cascades in b.c.c. Fe containing Y_2O_3 NPs corroborates aspects of the Ostwald ripening mechanism [56]. For example, MD predicts that when an irradiation damage cascade is initiated near a NP, the oxide/matrix interface arrests the cascade propagation, and the cascade energy instead induces partial amorphization of the Y_2O_3 NP [56]. Considering this result in light of the Ostwald ripening mechanism, it follows that: (a) amorphization of smaller NPs could promote their dissolution, and (b) amorphization of larger NPs at the oxide/matrix interface could make these interfaces a stronger sink [57] for Y, Ti, and O that has been solutionized from smaller NPs.

3.3 Irradiation-enhanced diffusion

The defect supersaturation produced by irradiation, in excess of defect concentrations dictated by thermal equilibria, lead to the irradiation enhancement of diffusion processes [48]. Irradiation-enhanced diffusion of sufficiently mobile species occurs either through vacancies or interstitials, and can significantly alter NP sizes and stoichiometries. Atomic species in solution – possibly in solution due to ballistic ejection from NPs – will either: (1) cluster together to nucleate new NPs, or (2) diffuse to existing NPs [48]. Likewise, atomic species in NPs can also diffuse out of the NPs if the chemical gradients make it possible. Therefore, the irradiation-enhanced diffusion mechanism must consider both growth and shrinkage of NPs, depending on chemical composition gradients. Quantifying this mechanism requires precise knowledge of chemistry in both the matrix and the oxide NPs.

The importance of the irradiation-enhanced point defect diffusion mechanism for NP evolution was notably demonstrated by Monnet, *et al.* [20]. The team observed stable NP chemistry and size under He^+ ion irradiation, for which the majority of energy is lost through inelastic interactions in displacement cascades. Conversely, they observed significant NP dissolution under electron irradiation, which is dominated by high-efficiency Frenkel pair production. These contrasting results demonstrate the critical role of freely-migrating point defects, and their irradiation-enhanced diffusivity, in NP evolution [20].

Because irradiation is a non-equilibrium condition, irradiation-enhanced diffusion can produce NP compositions far from equilibrium. For example, Ribis, *et al.* [30], report that interstitial mediated diffusion leads to non-equilibrium Cr accumulation at sinks, including at NPs. They also observe Y, Ti, and O diffusion toward NPs, and the cumulative result is that a non-equilibrium YTiCrO NP composition is maintained. At the same time, studies also report diffusion of Y can drive non-stoichiometric $\text{Y}_x\text{Ti}_y\text{O}_z$ NPs to stoichiometric $\text{Y}_2\text{Ti}_2\text{O}_7$ [9], [58]. In the case of TiO_2 NPs, Y diffusion is believed to create a Y-rich shell around the existing NP, leading to a larger NP with unchanged stoichiometry at the NP core [58]. It is also believed that irradiation-enhanced diffusion can lead to the segregation of Si, Ni, and Mn toward oxide NPs [14].

3.4 Homogeneous nucleation

Homogeneous nucleation of Y_2O_3 precipitates in a ferrite matrix is thermodynamically possible, via the $2\text{Y} + 3\text{O} \rightarrow \text{Y}_2\text{O}_3$ reaction [59]. This process is mathematically described by the condensation or adsorption of solutes into a precipitate

embryo; the free energy nucleation barrier considers the solute supersaturation in the solid solution, atomic volumes, and interfacial (surface) energy between the nuclei and the matrix. Once the precipitate embryo surpasses the critical radius, precipitate growth can occur, but that must be described by another mechanism (e.g. Hin and Wirth [59] couple a model of homogeneous nucleation with a Gibbs-Thomson type model of Ostwald ripening).

Homogeneous nucleation must necessarily be coupled to other NP evolution mechanism(s) because it cannot explain any NP behaviors beyond their formation to the critical radius. For example, the phenomenon of haloing [16], [17] is explained by a combination of ballistic dissolution and homogeneous nucleation: solutes ejected from existing NPs become supersaturated in the matrix, then nucleate into small NPs in the vicinity of the NP from which they were ejected. The experimental measurement of irradiation-induced bimodal NP size distributions, as noted in references [14], [23], [29], also supports the combination of ballistic dissolution and homogeneous nucleation mechanisms. Studies reporting an increased NP number density can also be thought to be consistent with the homogeneous nucleation mechanism.

3.5 Multiple active mechanisms

The irradiation evolution of NPs measured by experiments is not consistent with any single proposed mechanism. For example, ballistic dissolution on its own, will result in complete destruction of NPs over extended operating periods. Ostwald ripening, on the other hand, will result in continued coarsening of NPs. Finally, under irradiation-enhanced diffusion, NPs will eventually reach a steady-state morphology, determined by

the matrix and NP compositions. Clearly, none of these mechanisms alone can comprehensively explain the experimental observations of NP irradiation evolution. Rather, a combination of these mechanisms must be active in order to explain experimental results. For example, coupling of ballistic dissolution with Ostwald ripening and/or irradiation-enhanced diffusion can support the high-temperature stability of NP size observed in refs. [10], [11], [13], [36], [37], [60].

The notion of multiple active mechanisms is consistent with the observation of ion beam-induced size refinement of embedded metallic NPs [61]–[65], which is an emerging research area in nanoelectronics. In such a context, the mechanism of NP size evolution has been described as “inverse Ostwald ripening”, and it consists of several steps: (1) ion beams cause solute ejection (i.e. ballistic dissolution) from larger NPs more readily than from smaller NPs; (2) ejected solutes nucleate (i.e. homogenous nucleation) into new NPs, which subsequently coarsen; (3) a steady-state NP size, which is smaller than the original NP size, is achieved over time due to the competition between dissolution and coarsening. Inverse Ostwald ripening is therefore consistent with the idea that the fundamental mechanisms of ODS NP evolution described in this manuscript, all act in parallel.

Thus far, the most thorough effort to combine the effects of multiple mechanisms was recently carried out by Chen, *et al.* [8]. They coupled the Gibbs-Thomson model of Ostwald ripening with ballistic dissolution. Their model predicts that over time, the two competing mechanisms arrive upon an equilibrium state, beyond which NP size remains constant through high irradiation damage levels. However, this model does not consider the effects of irradiation-enhanced diffusion. A systematic experimental approach,

coupled with a more comprehensive mechanistic modeling effort, is imperative to advance the scientific community's understanding of oxide NP irradiation evolution.

4. Conclusions

We summarize all known experimental studies on ODS NP evolution under irradiation. Given the widely inconsistent experimental parameters, it is unsurprising that the results are likewise inconsistent and difficult to interpret *en masse*. We attempt to make more sense of the body of results by separately considering size and number density, chemistry, and crystal structure. The NP size and number density have both been found to increase, decrease, and remain stable with irradiation. Aside from some studies reporting a steady-state NP size at ~50 dpa, there is otherwise no apparent correlation between the direction of NP size and number density changes, irradiation dose, and irradiation temperature. With respect to chemistry, the Y:Ti ratio tends to decrease at irradiation temperatures $>500^{\circ}\text{C}$, and remain stable or increase $<500^{\circ}\text{C}$. The (Y+Ti):O ratio does not appear correlated with temperature, although it tends to change (either increase or decrease) at doses $\gtrsim 100$ dpa. Finally, with respect to the crystal structure, irradiation tends to cause the oxide/matrix interfaces to become more diffuse, and for faceted structures to become more spherical.

We also describe four fundamental mechanisms for ODS oxide NP evolution under irradiation: ballistic dissolution, Ostwald ripening, irradiation-enhanced diffusion, and homogeneous nucleation. However, no single mechanism alone can explain the

experimental results of irradiation evolution of ODS NPs. Rather, the experimental evidence suggests that multiple mechanisms are active in controlling the irradiation evolution of ODS NPs. Thus, in order to develop truly predictive capabilities for the long-term irradiation performance of ODS NPs, a systematic experimental study must be coupled with a model that comprehensively considers the combined effects of all fundamental NP nucleation and stability mechanisms described herein.

Acknowledgements

The authors acknowledge the support of the US Nuclear Regulatory Commission Grant NRC-HQ-84-14-G-0056; the US DOE, Office of Nuclear Energy under DOE Idaho Operations Office Contract DE-AC07-05ID14517, as part of Nuclear Science User Facilities experiments 14-485, 14-486, 15-540, and 16-710; the Idaho National Laboratory/Center for Advanced Energy Studies LDRD Program (KHY); the Micron Foundation and Boise State University Graduate College (MJS); and startup support from Purdue University (JPW).

Table 1. Nominal compositions of ODS alloys in wt%; balance is Fe (n.s. = not specified).

[illegible]

Table 2. Summary of previous studies of oxide nanoparticle evolution from the open literature (alloy type F = ferritic, M = martensitic, F/M = duplex ferritic/martensitic; n.s. = not stated).

Material	Type	Irrad. Particle	Irrad. Temp. (°C)	Irrad. Dose (dpa)	Dose Rate (dpa/s)	Method	Structure	Chemistry	Size	Number Density	Ref
F94	F	Fast n	400-530	2.5-15		TEM	n.s.	n.s.	Stable	Stable	[24]
MA957	F	Fast n	325	6		TEM, SANS	n.s.	n.s.	Stable	n.s.	[66]
9Cr ODS	M	Ni ⁺	500- 700	5, 50, 150	1.4 x 10 ⁻³	HR-TEM	n.s.	n.s.	Decrease	Increase	[7], [67]
MA957	F	He ⁺ + Ni ⁺	450, 650	150	2 x 10 ⁻³	TEM	n.s.	n.s.	Stable	Stable	[68]
MA957	F	Fast n	412-670	109-113		APT	n.s.	Stable	Stable	Stable	[69]
9Cr ODS	F	H ⁺	525	1	5 x 10 ⁻⁶	APT, EFTEM	n.s.	Stable	Decrease	Decrease	[70]
14YWT	F	H ⁺	400	1, 3	5 x 10 ⁻⁶	EFTEM	n.s.	n.s.	Increase	Increase	[11]
14YWT	F	Ni ²⁺	-75-600	5, 50, 100	2 x 10 ⁻³	APT	n.s.	n.s.	Decrease at T _{irr} < 600°C; else stable	Stable	[11]
14YWT	F	Ni ²⁺	-75-600	5, 50, 100	2 x 10 ⁻³	EFTEM	n.s.	n.s.	Increase	Decrease for T _{irr} ≤ 300°C; else increase	[11]
14YWT	F	Fast n	500	3	1 x 10 ⁻⁷	APT, EFTEM	n.s.	n.s.	Decrease	Increase	[11]
12Cr ODS	F/M	Fe ²⁺	325-625	100, 200	n.s.	HRTEM	Larger phases lose coherency	n.s.	Decrease	Decrease	[8]
12Cr ODS	F/M	Fe ⁸⁺ + He ⁺ + H ⁺	21	4.4		EFTEM	n.s.	Stable	Stable	Stable	[71]
9Cr ODS	F	Fe ²⁺	400	50	1 x 10 ⁻⁴	APT	n.s.	n.s.	Stable	Decrease	[72]
DY	F	Fast n	400-580	81		TEM	Halo; irregular O/M interfaces	Ti, Al loss	Decrease	Decrease	[16]
14YT	F	Fe ³⁺	700	50		APT	n.s.	Y:Ti decrease	Increase	Increase	[25]
14YWT	F	Ni ²⁺	300-600	100	1.39 x 10 ⁻²	APT	n.s.	Y:Ti increase at 300°C	Decrease	Decrease	[18]
9Cr ODS	F	H ⁺	400	3.7	0.5 x 10 ⁻⁵	APT	n.s.	Y:Ti increase	Increase	Decrease	[19]
MA957	F	He ⁺ + Ni ⁺ , C ⁻	475- 625	200	3.0-14 x 10 ⁻³	TEM	n.s.	n.s.	Stable	Stable	[73]
9Cr, 12Cr ODS	M, F	Fast n	420-835	28-51		TEM	n.s.	n.s.	Stable	Stable	[74]
MA957	F	Fe ⁺	25	18		TEM	Amorphize	n.s.	Stable	n.s.	[42]

MA957	F	Kr ⁺	500	200		TEM	Stable	n.s.	Stable	n.s.	[42]
K6	F	n.s. ion	300-700	20	9.9×10^{-5}	HRTEM	n.s.	n.s.	Stable	Stable	[75]
K1, K4	F	Fe ³⁺	500-700	20, 150	1×10^{-3}	STEM	n.s.	n.s.	Stable	Stable	[76]
SOC-1	F	Fe ³⁺	650	60	5×10^{-4}	STEM	n.s.	Stable	Stable	Stable	[77]
18Cr ODS	F	Fe ⁺	500	4-45		EFTEM	Interfaces become irregular		Stable	Stable	[39]
18Cr ODS	F	Fe ⁺	500	150		APT, EFTEM	n.s.	Approaches Y ₂ Ti ₂ O ₇ stoich.	Increase	Decrease	[9]
18Cr ODS	F	Au ²⁺	RT	156		APT, EFTEM	Amorphization	n.s.	Dissolution	Dissolution	[9]
9Cr-2W ODS	M	e ⁻	400			TEM	Amorphization	n.s.	Decrease	Decrease	[44]
DY	F	Cr ⁶⁺ + He ⁺	475	50	3.0×10^{-4}	TEM	Complex oxides not observed	n.s.	Stable	n.s.	[78]
F82H, 16Cr ODS	F	Fe ³⁺	380	20	1.1×10^{-3}	HRTEM	n.s.	n.s.	Decrease	Decrease	[79]
14Cr ODS	F	Fe ³⁺	Cryo - 700	15	3×10^{-3}	GIXRD	Stable	n.s.	Dissolution at cryo; else decrease or stable	Dissolution at cryo; else decrease or stable	[13]
MA957	F	Therm. n	325	2.0, 5.5	2.9×10^{-7}	TEM, SANS	Stable	n.s.	Stable	Stable	[80]
DY	F	Fast n	400-480	75.4		XAFS, TEM	Disordering	n.s.	Decrease (larger oxides)	Not Specified	[35]
MA957	F	Fast n	600	3	3.7×10^{-7}	APT	n.s.	Y:Ti decrease	Stable	Stable	[26]
DY	F	Kr ¹⁸⁺	RT			STEM	Amorphize		Stable	Stable	[45]
EM10 ODS	F	e ⁻	300-500	100	$3-6 \times 10^{-3}$	HRTEM	n.s.	Stable	Decrease	n.s.	[17]
DY, EM10 ODS	F	He ⁺	400	0.05		HRTEM	n.s.	Stable	Stable	Stable	[20]
DY, EM10 ODS	F	Ar ⁺	400	33		HRTEM	Amorphize	n.s.	Decrease	Decrease	[20]
DY	F	Fast n	400-580	≤81		HRTEM	Halo	Al, Ti loss < 70 dpa; else stable	Decrease > 70 dpa	Decrease >70 dpa	[20]
DY, EM10 ODS	F	e ⁻	300-550	33	$3-6 \times 10^{-3}$	HRTEM	n.s.	Stable	Decrease	Decrease	[20]
12YWT	F	Fe ⁺	300	0.7	1.9×10^{-4}	APT	n.s.	Stable	n.s.	Stable	[81]
12Cr, 14Cr ODS	F	Fe ³⁺ + He ⁺ + H ⁺	RT, 600	10-30	1×10^{-3}	PAS	Vacancy cluster-Cr complexes	n.s.	Stable	n.s.	[54]
14LMT	F	Fe ²⁺	30	10-100		APT, EFTEM	n.s.	Stable	Stable	n.s.	[29]
14LMT	F	Fe ²⁺	500	10-100		APT, EFTEM	n.s.	Cr, La pickup	Decrease	Stable	[29]
Eurofer 97 ODS	F/M	H ⁺	40	0.3, 1, 2		TEM	Amorphize particles <20 nm	n.s.	n.s.	Stable	[46]

18Cr ODS	F	Xe ⁺	27, 500	2.5		TEM	Amorphize at T _{irr} =27°C	n.s.	Increase at T _{irr} =27°C; else stable	n.s.	[47]
MA957	F	Fe ⁺	500	150	6.5 x 10 ⁻⁴	HRTEM, EFTEM	Stable	n.s.	Increase	Decrease	[10]
MA957	F	Fast n	412, 430	50, 75	1.3 x 10 ⁻⁷	HRTEM, EFTEM	Stable	n.s.	Stable at T _{irr} =412°C; else increase	Stable at T _{irr} =412°C; else decrease	[10], [36], [37]
14Cr ODS	F	Fe ⁺	500	150		EFTEM	n.s.	Stable non- stoich.	Increase	Decrease	[30]
Fe-Y ₂ O ₃ ODS	F	Fe ⁺ with/out He ⁺	500, 600	100		TEM, SANS	n.s.	n.s.	Stable at T _{irr} =500°C; else increase	Stable	[60]
Eurofer 97 ODS	F	Fast n	330	32		APT, TEM	n.s.	V loss, Y pickup	Dissolution (of particles > 10 nm)	Increase	[21], [22]
Eurofer 97 ODS	F	Fe ⁺ , Fe ²⁺ , Fe ³⁺	RT	32		APT, TEM	n.s.	V, N Loss	Dissolution	Stable	[82]
Eurofer 97 ODS	F	Fe ²⁺ and Ti ²⁺	RT	0.8-0.9		APT, TEM	n.s.	Y, O, Mn pickup	Decrease	Increase	[23]
13.5Cr ODS	F/M	Ti ²⁺	RT, 300	0.8-2.4		APT, TEM	n.s.	O pickup; Y:Ti decrease	Stable	Increase	[23]
13Cr ODS	F	e ⁻	400, 500	12	2.2 x 10 ⁻³	TEM	n.s.	n.s.	Difficult to discern	Difficult to discern	[83]
14Cr ODS	F	Fe ⁵⁺ + He ⁺ + H ⁺	600	30		EFTEM	n.s.	Stable	Increase	Stable	[84]
Eurofer 97 ODS	M	H ⁺	40, 350	0.3-2.0		TEM	n.s.	n.s.	Stable	Stable	[85]
Cr16 ODS, EP450	F	Bi ⁺ , Xe ⁺	350-650			HRTEM	Amorphous ion tracks	n.s.	Decrease for T _{irr} >600°C	Stable	[41]
EP450	F	Xe ⁺ , Kr ⁺ , Ar ⁺	RT			HRTEM	Amorphous ion tracks	n.s.	n.s.	n.s.	[86]
9Cr ODS	F	H ⁺	500	3	1 x 10 ⁻⁵	APT	n.s.	Stable	Decrease	Stable	[14], [15]
9Cr ODS	F	Fast n	500	3	1 x 10 ⁻⁷	APT	n.s.	Y:Ti increase; (Y+Ti):O stable	Decrease	Decrease	[14], [15]
Eurofer 97 ODS	M	Fe ²⁺	400	2	~1 x 10 ⁻⁴	APT	n.s.	Stable	Stable	Stable	[31]
1DS	M	Fast n	450-560	10.5-21		TEM	n.s.	n.s.	Decrease	Decrease	[27]
1DK	F	Fast n	450-560	10.5-21		TEM	n.s.	Y:Ti decrease	Increase	Decrease	[27]

F95	F	Fast n	400-530	2.5-15		HRTEM	Stable	Y:Ti decrease for $T_{in} \geq 500^{\circ}\text{C}$	Stable	Stable	[24], [28]
M93	M	Fast n	400-530	2.5-15		HRTEM	Stable	Y:Ti decrease	Stable	Stable	[24], [28]
MA957	F	Fast n	500, 700	100	1.2×10^{-6}	TEM	n.s.	n.s.	Increase	Decrease	[38]
16Cr ODS	F	e^{-}	500	10		TEM	Stable	n.s.	Decrease	Stable	[55]
K3	F	Fe^{3+}	300, 500	1-10	1×10^{-3}	TEM	n.s.	n.s.	Stable	Stable	[87]
12.5Cr ODS	F	$e^{-} + \text{H}^{+}$	350-550	15	2×10^{-3}	TEM	O/M interface becomes irregular	n.s.	Stable	Stable	[40]
9Cr ODS	F	Fe^{2+}	500	3, 100	1×10^{-4}	APT	n.s.	n.s.	Decrease	Decrease	[12]
PM2000	F	Fast n, He^{+}	500	21		EFTEM	Amoprization; faceted shape becomes spherical	Cr-rich shells	n.s.	n.s.	[88]

Figure 1. NP size evolution with increasing irradiation dose; data gathered from several studies.

Figure 2. Results from the open literature indicating the direction (i.e. increase, decrease, or stable) of the irradiation-induced change in: (a) NP size, (b) number density, and (c) volume fraction.

Figure 3. Results from the open literature indicating the direction (i.e. increase, decrease, or stable) of the irradiation-induced change in: (a) Y:Ti ratio and (b) (Y+Ti):O ratio.

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