Advanced Additive Manufacturing of Y_2O_3-Enhanced Dispersion Strengthened Steel

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Abstract. Oxide dispersion strengthened (ODS) alloys represent a cutting-edge solution for high-temperature applications, with enhanced mechanical properties achieved through the fine dispersion of oxide particles in a metallic matrix. These alloys are critical in industries such as gas turbines and nuclear reactors, where materials must withstand high temperatures and have high strength and creep resistance. Yttria oxide (Y_2O_3) is particularly effective in distributing nano-scale oxide particles, significantly enhancing the material's thermal stability, oxidation resistance, and overall strength. Additive manufacturing (AM) technologies, such as selective laser melting (SLM), offer a novel route to streamline ODS steel production, allowing for efficient, complex component fabrication with improved control over material properties. This paper explores the role of Y_2O_3 in strengthening ODS steel and highlights the potential of AM techniques to revolutionize ODS manufacturing. A case study on the fabrication of 316L stainless steel with varying Y_2O_3 content using SLM is also reviewed, emphasizing the benefits and challenges of integrating Y_2O_3 in the AM process.

Keywords: Oxide dispersion strengthened, additive manufacturing, selective laser melting.

1. Introduction

Stainless steel's strong corrosion resistance and mechanical properties have made it a primary material in a lot of industrial fields, including petroleum, chemical industry, machinery, and nuclear power. Due to the intergranular corrosion of pure stainless steels with stress corrosion cracking and corrosion fatigue, oxide dispersion strengthened (ODS) steel is widely developed. Experts around the globe have paid attention to ODS as a major material for the next generation of nuclear reactors [1]. Generation IV systems provide carbon-free energy solutions, like the sodium-cooled fast reactor (SFR), which is an advanced sodium technological reactor for industrial demonstration. Advanced sodium technological reactor for industrial demonstration (ASTRID) prototype is developed to offer carbon-neutral energy alternatives. In these reactors, fuel claddings serve as critical safety barriers, shielding against radioactive fuel release. These claddings must endure extreme conditions, including temperatures as high as 700°C, strong neutron radiation, and extended exposure times. They also handle increased fuel burn-up as high as ~100 MWd/kg to ensure both safety and economic efficiency in plant operation. Therefore, ODS alloy's properties provide a solution for these demands and are seen as promising candidate materials for these applications [2].

To further hinder grain growth, grain boundary migration, and dislocation movement, yttrium oxide (Y_2O_3) can be added to the matrix. Thus, the materials performance is enhanced. However, Y_2O_3 is observed to be insoluble in the austenite matrix, which means that manual breaking of Y_2O_3 particles and embedding them in the matrix in the form of fine fragments under the collision of ball milling is required. As a result, Y_2O_3 particles will have nonuniform size distribution and irregular shape. The reactive-inspired ball-milling (RBM) method is developed to generate fine, uniform Y_2O_3 particles. In this process, reactants are ground together during ball-milling, which causes molecular splitting and atomic recombination, leading to small-scale nucleation of Y_2O_3 particles. Subsequent annealing further increases the density of these particles. This method has been used to introduce Y_2O_3 into alloys, and it has the potential for large-scale industrial production of ODS steels. The 316L steel is highly regarded in the engineering field for its corrosion resistance and excellent toughness. However, it could only be used in wider applications with a higher strength, which led to the attempt to prepare an ODS-316L steel by introducing oxides into the 316L steel matrix [3]. Additive manufacturing (AM) provides the most convenient way for manufacturing ODS alloys in terms of both cost and human control level.

Furthermore, AM is adapted to a wide variety of industries like aerospace, automotive, energy and biomedical branches. Fig. 1 shows the use of AM to create ODS materials for the energy and aerospace industries, including nuclear fusion reactors and turbofan engines. The process involves producing tailored composite powders and refining parameters for efficient production. Techniques like scanning electron microscope (SEM), computer tomography, and electron backscatter diffraction are used to analyze the materials' microstructure and mechanical properties. As a result, intensive research activities in areas highlighting the demand for new material concepts designed for AM allow the conclusion that not only can AM be used in improving the production of existing ODS materials but also that ODS can help exploit new possibilities of AM [1].

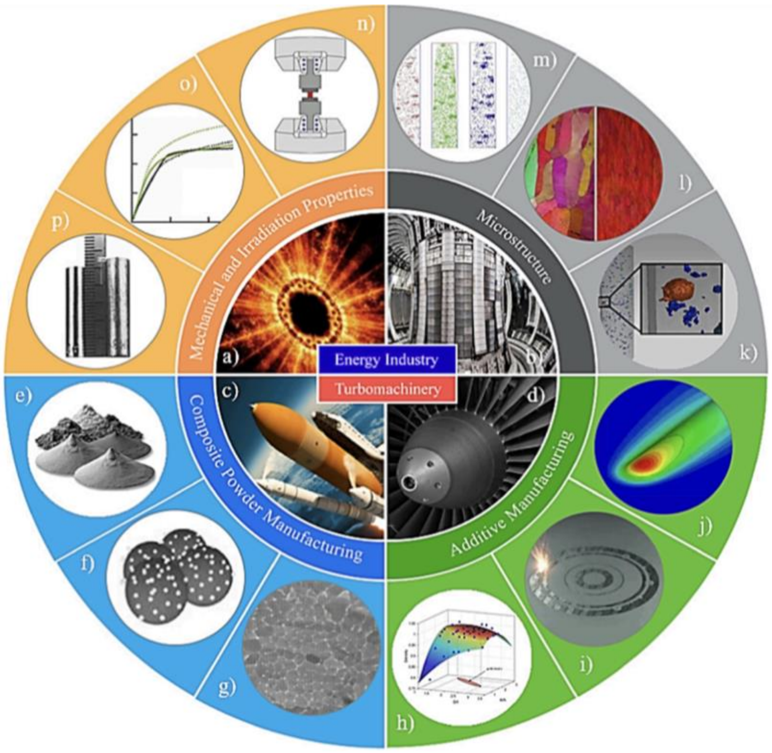

Figure 1. AM of ODS materials [1]

2. Y_2O_3-Strengthened ODS Alloys

2.1. Benefits of ODS Alloys in Irradiation Environments

Advanced copper alloys have been used in high-heat flux and high-temperature applications. Effective performance requires these materials to have high thermal conductivity, which is around 300-400 W/mK; good mechanical properties with yield strength larger than 200 MPa; and high irradiation resistance. Precipitation-strengthened (PS) copper alloys and dispersion-strengthened (DS) copper alloys fulfilled the first two requirements but not the latter. ODS alloys have good mechanical properties and irradiation resistance and are, therefore, the most suitable for irradiation environments. Fig. 2 depicts the Orowan mechanism in ODS alloys, where scattered nanoparticles are seen both during and after interaction with a dislocation line (red box and green box) [3].

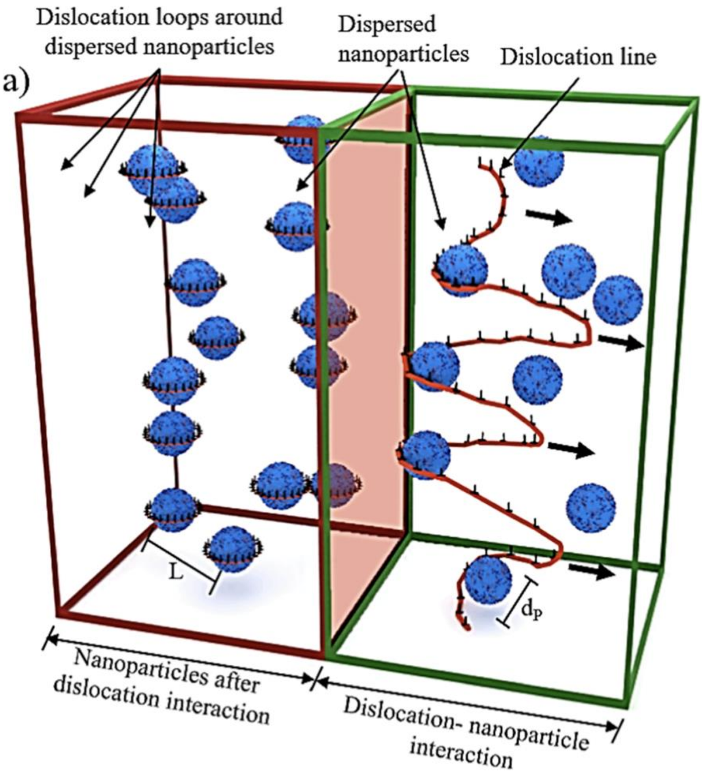

Figure 2. Scheme of the Orowan mechanism in ODS alloys [2]

Furthermore, because of the ability of the dispersed oxide nanoparticles to stop dislocation and grain boundary movement and trap radiation-induced defects, the ODS ‘s ability to hinder the mechanical properties and good irradiation resistance. By incorporating Y_2O_3 during HIP, an ODS steel with the ultra-high number density of Y_2O_3 oxide nanoparticles could be successfully prepared; hot rolling afterward improved the microstructure and properties. After adding Y_2O_3 powder and hot rolling, ODS steel with an exceptional combination of strength (1474 MPa) and ductility (13%) was produced. The reaction between Y and the remaining oxygen in the tank causes the presence of Y_2O_3 oxide nanoparticles in H-1, which have a large particle size and low number density. On the other hand, the addition of Y_2O_3 powder to H-2 results in the formation of oxide nanoparticles with a very high number density. After hot rolling, the particle size of Y_2O_3 did not significantly increase, indicating that it has exceptional thermal stability [4].

Oxide nanoparticles with a very high number density are formed when Y_2O_3 powder is added to H-2. Y_2O_3's particle size did not considerably increase following hot rolling, demonstrating its exceptional thermal stability.

2.2. Challenges Associated with the Hot Isostatic Pressing (HIP) Process

One critical challenge when manufacturing ODS alloys is Yttrium loss during the HIP process. When the temperature reaches temperatures between 1100–1300°C and a high level of pressure, yttrium atoms (particularly in the form of Y_2O_3) will diffuse out of the material. In some cases, yttrium atoms migrate to grain boundaries during HIP processing. This phenomenon can create localized regions with lower concentrations of yttrium oxide, reducing the uniformity and effectiveness of dispersion strengthening [4]. The uniform distribution of yttrium oxide particles is essential for the high-temperature strength of ODS alloys. Yttrium loss reduces the amount of these fine oxide particles, leading to a decrease in the alloy’s ability to resist deformation at elevated temperatures [5]. In addition, Without the pinning effect provided by the fine yttrium oxide particles, grains in the alloy can grow larger, further weakening the material by reducing its creep resistance and making it more prone to failure under stress.

3. Production of ODS through AM

AM offers several benefits for producing ODS alloys. In AM, a laser or electron beam melts metal powder particles and fuses them to form the object's design. AM is one of the promising routes with layer-by-layer manufacturing and enables design flexibility. Because of this, the majority of AM technologies commonly use powder or wire as a feedstock, which is selectively then melted by a concentrated heat source like a laser beam and consolidated in subsequent cooling to form a part. The primary advantage of AM lies in its ability to create parts with highly complex geometries directly from CAD data, significantly reducing waste compared to traditional manufacturing methods. This saves time from designing a part and also saves material, given that metallic products are based on expensive and scarce alloy elements [1]. Nowadays, there are more options to manufacture metals and characteristics of the composite powder material. Conventional metallurgical processes, like casting, are unsuitable for producing ODS alloys due to nanoparticle agglomeration and flotation, which prevent uniform oxide dispersion. AM, with its quick solidification and dynamic melt flow, effectively suppresses these issues, making it a feasible method for producing ODS alloys [6].

However, careful management still needed to be taken when printing fabrication of ODS materials with AM techniques. It requires a careful choice of powder manufacturing processes, process design, and the subsequent correlation of mechanical properties with microstructural features. In addition, absorption and reflection are significantly influenced by the powder species and properties of the composite powder material, such as the structure and particle size distribution and surface condition [6]. A key challenge in using AM for forming ODS alloys lies in the behavior of nano-oxide particles during the melting process. When exposed to high-energy irradiation, the metal component melts, while the oxide particles tend to agglomerate due to their small size and high surface energy. Van der Waals forces drive this agglomeration and can lead to particle flotation, forming slag layers on the melt pool surface. This can result in uneven distribution of the oxides and negatively affect the alloy's properties [7]. Controlling these dynamics, including the complex flow conditions and particle movement, remains a challenge due to the difficulty of directly observing nanoparticle behavior in real time. Sometimes, spherical powder morphologies are essential for processing metallic powder materials in AM in a successful way due to their excellent flowability properties that are needed for the powder deposition and recoating process.

4. Dense ODS Steel Production

Selective laser melting (SLM), one of the most widely used AM technologies, can be used to evaluate the impact of Y_2O_3 on the microstructure and mechanical characteristics of 316L. The spherical powders 316L covered with a Y_2O_3 layer have been prepared and successfully used to prepare specimens via SLM [8]. Regardless of the amount of Y_2O_3 doping, the grain morphology and crystallographic texture of the specimen exhibit the same anisotropy in both vertical and horizontal directions. The tensile properties of 316L stainless steel are significantly enhanced after doping with Y_2O_3. The ultimate tensile strength (UTS) increases from 707 ± 3 MPa in the undoped specimen to 750 ± 8 MPa in the 0.5 wt% Y_2O_3-316L specimen, showing a marked improvement. However, the ductility decreases with higher Y_2O_3 content, dropping from 42.5 ± 0.3% (undoped) to 24 ± 0.6% in the 1 wt% Y_2O_3-316L specimen. The 0.25 wt% Y_2O_3-316L specimen, however, breaks the typical strength-ductility trade-off, achieving a UTS of 732 ± 5 MPa while maintaining the highest ductility at 49.5 ± 0.8%. There are two main mechanisms of strengthening: the first is the action of the doped Y_2O_3, and the second is the effect of the produced twins. The twin boundaries (TBs) formed in the specimen can block the movement of dislocations during the plastic deformation process [9]. In addition, similar to grain boundary strengthening, TBs offer a significant amount of area for the aggregation and storing of dislocations during the plastic deformation process.

However, the ball milling process is typically used in the mixing process of the second phase particles and the original spherical matrix powder of the second phase. This can cause the matrix powder to lose its shape, oxidize, and agglomerate the second phase particles, which would greatly destroy the mixed powder's sphericity and cause the particles in the molded part to agglomerate [10]. To address ball milling's limitation, in this study, spherical 316L powder coated with a Y_2O_3 layer was prepared using an in-situ chemical generation method. This approach minimizes particle agglomeration and preserves the spherical shape of the matrix powder. The effects of Y_2O_3 on the microstructure and mechanical properties of 316L steel were then investigated, focusing on the evolution of microstructure and the mechanisms behind the strengthening in both 316L and ODS 316L specimens.

5. Conclusion

Integrating Y_2O_3 into ODS steels offers several key advantages. The nano-sized Y_2O_3 particles help improve the high-temperature strength and creep resistance of the steel by impeding dislocation movement within the matrix. Y_2O_3 also enhances the material's oxidation and corrosion resistance, making ODS steels particularly useful in extreme environments like nuclear reactors and high-temperature applications. AM methods provide an encouraging replacement for the conventional ODS alloy production chain. Due to the shorter process chain---combining synthesis and shaping in a single process step---the economic production of ODS alloys by AM becomes attainable. Few studies studied multiple AM processes utilizing identical powder feedstocks to offer a comparative assessment of different AM technologies. As a result, important details on critical factors regarding the powder properties of the powder feedstock used and process-related conditions, like process parameters and solidification conditions, still need to be found.

Additionally, there have been insufficient studies implemented on the impact of morphology, rheology, and nanoparticle distribution in manufactured composite powder materials on the process conditions of various AM techniques. A lot of AM-manufactured ODS are weaker than conventionally manufactured ones. Future potential solutions include using short-term energy inputs, applying acoustic waves, beam shaping, and advanced scanning strategies to enhance melt pool dynamics and prevent nanoparticle agglomeration. Also, adding elements like zirconium or hafnium could encourage the formation of smaller, more stable oxide particles and can, therefore, alter the chemical composition of the matrix alloy. Laser-based fragmentation can also help reduce initial nanoparticle size and limit agglomeration.

Despite existing challenges, additively manufactured ODS alloys frequently show better properties than non-reinforced reference materials, especially in high-temperature environments. This makes ODS a highly promising approach for advancing AM materials.

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