Advanced Manufacturing of Oxide-Dispersion-Strengthened Alloys for Next-Generation Nuclear Energy Systems

Xueliang Yan[1], Fei Wang[1], Yongfeng Lu[2], Michael Nastasi[3], Bai Cui[1]

[1]Department of Mechanical & Materials Engineering, University of Nebraska–Lincoln., [2]Department of Electrical Engineering, University of Nebraska–Lincoln, [3]Nebraska Center for Energy Sciences Research, University of Nebraska–Lincoln

Motivation

- Due to the high operation temperatures of generation-IV nuclear energy systems and aeronautical engines in the United States, industrial components must be made from materials that have outstanding mechanical properties in high-temperature environments.
- Oxide-dispersion-strengthened (ODS) alloys are promising for the high-temperature environments due to their unique microstructures of nanosized oxide particles in stainless steels. During the advanced manufacturing process, ODS alloys need to be joined to make industrial components.
- **The goal of this research** is to develop advanced manufacturing methods to produce ODS alloys and their joints.

Introduction

- ODS alloys have a homogenous dispersion of nanosized oxide particles in the metal matrix, which result in high strength and creep resistance at high temperatures. The dispersion of oxide nanoparticles can impede the motion of dislocations and reduce grain coarsening, improving the thermomechanical properties at elevated temperatures.
- We have developed a powder metallurgy process to manufacture ODS alloys, which consists of mechanical alloying by high energy ball milling, followed by spark plasma sintering (SPS). SPS can provide very fast sintering rates when applying uniaxial pressure and high-intensity pulsed direct current, resulting in higher density, smaller grain size and cleaner grain boundaries.
- ODS alloys need to be joined to make industrial components. However, traditional joining process causes the coarsening and aggregation of dispersion particles, leading to the deterioration of the joint's mechanical strength.
- This project will develop a novel pulse electric current (PEC) process for the joining of oxide-dispersion-strengthened alloys, which can overcome existing challenges. The PEC joining process involves simultaneously applying a pulsed electric current and a uniaxial pressure to mechanical alloying powders placed between two ODS alloy parts, producing a solid-state bonding (Fig. 1). Because the PEC process avoids the melting or excessive heating of ODS alloys, it will result in minimal changes of the microstructure of oxide dispersion in the ODS alloy joints.

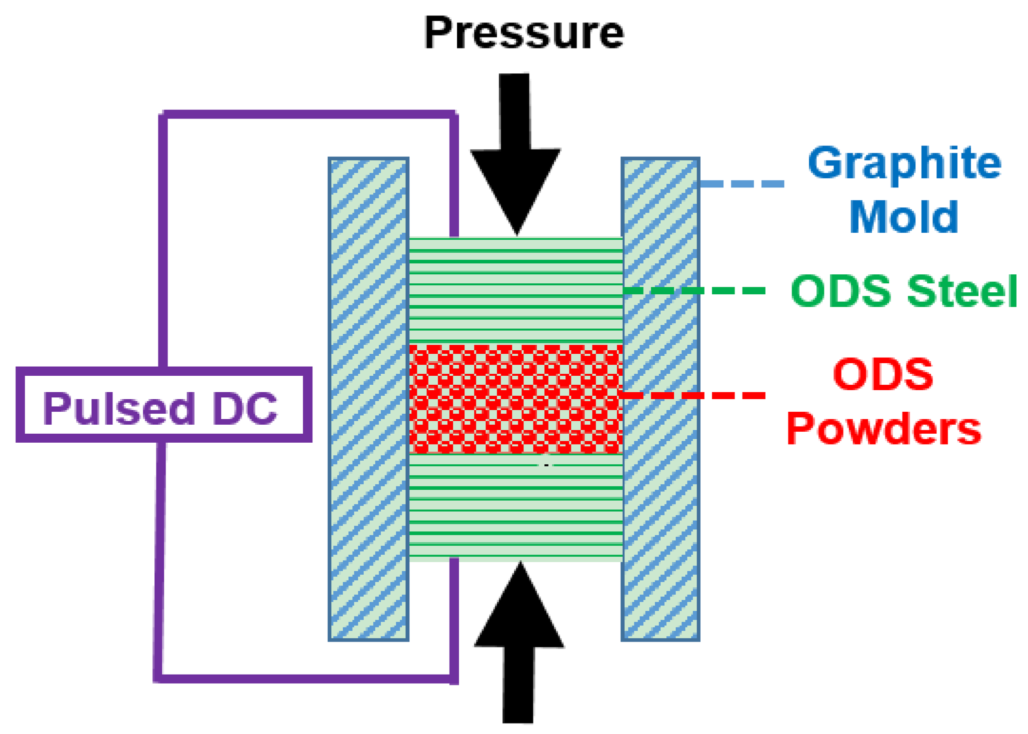

Fig. 1. Schematic of the PEC joining of ODS alloys.

Results

I. Manufacturing of ODS alloys

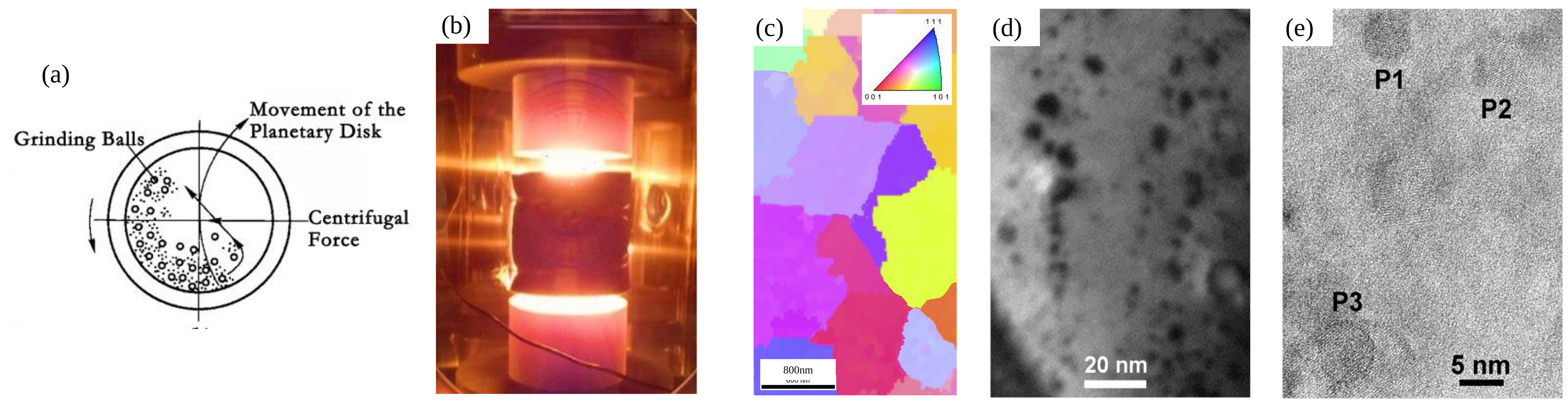

Fig. 2. Illustration of (a) ball milling and (b) SPS; (c) Electron backscatter diffraction (EBSD), (d) Bright-field and (e) High-resolution transmission electron microscopy (HRTEM) images of ODS 304 alloys (Fe-18Cr-8.5Ni-2W-0.5Ti-0.35Y_2O_3).

- ODS 304 alloys were manufactured by powder metallurgy: mechanical alloying of the raw powders by high-energy ball milling and spark plasma sintering (SPS) at 1000 °C for 5 min.
- The grain size ranges from 100 nm to 1.5 μm (average size: 618 ± 324 nm), and nanoscale Y_2O_3 articles (< 10 nm) are homogenously dispersed in the 304 alloy grains.

II. PEC joining of ODS alloys

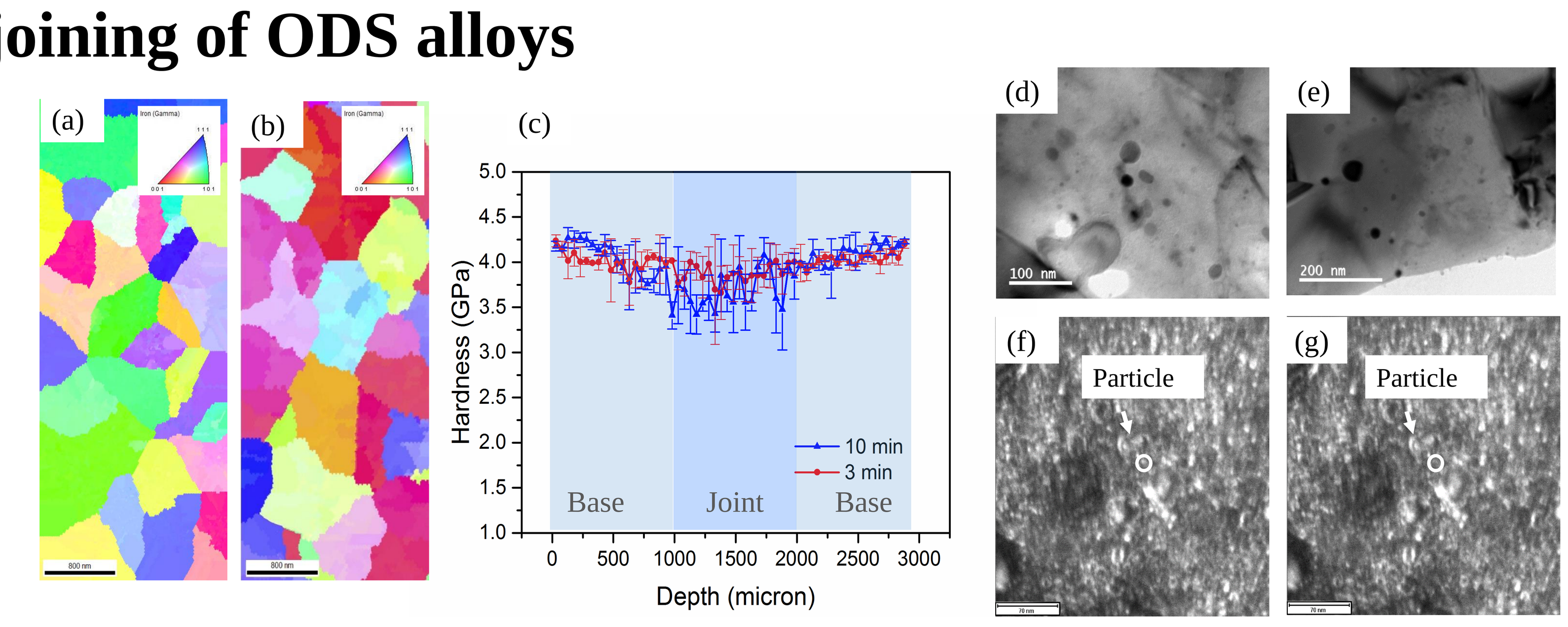

Fig. 3. (a-b): EBSD images of PEC joints with holding time of (a) 3 min and (b) 10 min; (c): The microhardness of the cross-section of PEC joints with holding time of 3 min and 10 min; (d-e): Bright-field TEM images of the microstructures PEC joints with holding time of (d) 3min and (e) 10 min; (f-g): Dark-field TEM images of a zone in the joint with dispersed oxide particles, showing the dislocation loop indicated by the circle disappeared at the interface of the oxide particle pointed by the arrow at Au^{4+} irradiation of 2.1 dpa.

- The average grain size for the joints of 3 min and 10 min are 568 ±249 nm, and 643 ± 258 nm, which are quite small compared with other joining methods.
- The microhardness of the PEC joints is just slightly lower than that of the base area, whose average value is about 3.75 GPa compared with about 4.1 GPa of the base alloys.
- The fine oxides of Y_2O_3 are all dispersed uniformly in the joints of 3 min and 10 min. There is no evidence of melting can be observed at their interfaces. The average particle sizes of oxides in PEC joints are comparable to that in the base alloy, indicating the oxide particles in the bond layer did not undergo coagulation and coarsening.
- Dislocation loops can be annihilated at the interface between the oxide particle and the matrix of the joint, indicating that the oxide particles in the PEC joints were not degraded so that the irradiation resistance of the joints was not deteriorated compared with the base alloys.

Conclusions

- ODS 304 alloys were manufactured by spark plasma sintering (SPS). Nanoscale Y_2O_3 articles (< 10 nm) are homogenously dispersed in the grains whose average size is ~ 600 nm.
- The joining of ODS 304 alloys was completed by pulsed electric current (PEC) process. The grain size after PEC joining are close to the base alloy and quite small compared with other joining methods. The microhardness of the PEC joints is just slightly lower than that of the base area. The fine particles of Y_2O_3 are still dispersed uniformly in the joints, without melting, coagulation or coarsening.
- Dislocation loops can be annihilated by the oxide particles, meaning the particles were not degraded during the PEC joining.

Acknowledgements

This work was supported by the Nebraska Public Power District through the Nebraska Center for Energy Sciences Research.

LASER ASSISTED NANO ENGINEERING LAB (LANE)
DEPARTMENT OF ELECTRICAL ENGINEERING

University of Nebraska Lincoln | NEBRASKA CENTER FOR ENERGY SCIENCES RESEARCH

NCMN
Nebraska Center for Materials and Nanoscience
University of Nebraska