A novel approach to advanced nanostructured materials manufacturing

J. J. Graham[1], K. Sridharan[2], B. R. Maier[2], H. Yeom[2], P. Hosemann[1]

[1]*Nuclear Engineering Department, University of California Berkeley, Berkeley, CA*
[2] *University of Wisconsin, Madison, WI*

INTRODUCTION

The economic utility of a nuclear power plant is in direct proportion to the profitable lifetime of the plant. In this vein, new designs are being considered that have an expected operating lifetime of 60 years. [1] This will demand new materials capable of withstanding the extreme environment of a nuclear reactor for this duration. The high radiation environment, in particular, represents a great difficulty, as future materials are expected to receive doses of 200 dpa or greater, depending on reactor design [2]. These high doses can lead to void swelling, helium bubble development, and excessive embrittlement, all of which can lead to significant materials degradation.

One strategy to meet these requirements in future materials is to improve the rate at which these materials recover from damage. This can be achieved by increasing the rate of removal of point defects by increasing the number of sink sites, and the surface of a material is exceptional in this role [3]. It follows that nano-structured materials are a promising route of exploration: their vast surface-to-volume ratio provides an exceptional damage sink [4], without sacrificing other advantageous bulk properties [5].

This paper is part of an on-going effort to provide reliable and economical means of forming and shaping these materials, and hypothesizes that cold-spray forming is part of a viable path. A similar method for has been explored by Kreuzeder *et al*, that of mechanically forming an interlocked lattice of immiscible metals, followed by a chemical dissolution of one of the constituents. Thoroughly mixed iron and copper powders have been successfully compressed in a high-pressure torsion (HPT) apparatus to form such a system [6]. This does allow the formation of buttons and small samples, but is limited in the geometries it can produce. Cold spraying, an additive manufacturing processes, has the capacity for producing complicated geometries, and moreover has similarities to the demonstrated HPT technique that suggest it will be successful in forming these nanostructured materials.

HIGH PRESSURE TORSION

HPT is a forming mechanism that combines axial compressive loading with torsional strain, as depicted in fig. 1. The combination of these two deformation mechanisms allows for significant plastic deformation of the sample, effectively allowing material to flow and consolidate into a bulk material. At pressures of in the range of 6 GPa, this flow has been shown to produce internal grains of average size less than 100 nm [7]. As has been shown, this will enable the creation of Cu-Fe alloy microstructures [3]. This paper proposes that, for such alloying, HPT could be replaced by any mechanism that could create similar conditions of local material flow under flow under extreme pressure.

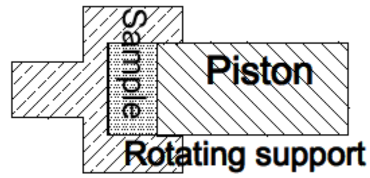

Fig. 1. Schematic of a notional high pressure torsion apparatus.

COLD SPRAY FORMING MATERIALS

The cold spray process has been in development for some years now as a means of applying coatings to surfaces without inducing heat damage in the deposited material or substrate. In this process the powder particles of the coating material are propelled at supersonic velocities onto the surface of a substrate to form a coating. More specifically, the powder is accelerated with a Laval nozzle, as shown in fig. 2 [8]. A particle traveling fast enough at impact may deform and adhere to other particles already deposited. Below a material-dependent critical velocity, the particle will not adhere to the substrate, while erosion is observed for impact velocities in excess of the critical velocity [9]. This velocity range has been shown to vary with mechanical properties of the material and substrate, but some general trends have been observed that offer guidance as to conditions favorable for deposition. In general higher deposition rates can be achieved by increasing pressure and gas preheat temperature [10, 11, 12]. Recent research at the University of Wisconsin, has effectively introduced the application of cold spray technology to the field of nuclear reactor materials by way of development of oxidation-resistant coatings for accident tolerant fuel development [12]. The low powder particle temperature allows for the preservation of any thermally-induced microstructural or phase changes during the deposition process.

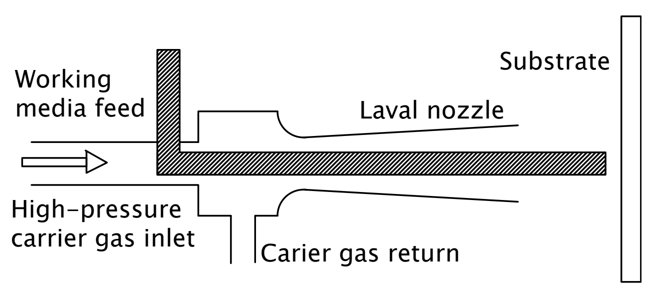

Fig. 2. A schematic representation of a cold-spray system such as the one at the University of Wisconsin that will be used in this research.

PRIOR WORK AND DISCUSSION

The high stresses induced by plastic flow in cold-spray deposited material has similarities to HPT processed material above, and therefore may yield similar structures particular in regards to creating nanostructured foams.

The University of Wisconsin and other cold-spray research programs have demonstrated the ability to deposit a wide range of metal powder coatings, including aluminum, iron, and titanium and their alloys. However, to spray multiple species simultaneously frequently poses challenges owing to variations in material properties. This paper assumes a heuristic model of deposition based upon material properties, especially hardness and ductility. Copper and iron are therefore expected to have optimal deposition in non-overlapping cold spray regimes, hindering their mutual formation.

Fundamental to success will be the establishment of a process in which Cu and Fe can be deposited simultaneously. Though it may be possible to utilize multiple spray nozzles in order to independently optimize size, velocity, and temperature properties for the copper and iron particles deposited, it would be significantly more advantageous to have a single powder mixture suited to the cold spray process. Mechanically alloying powder copper and iron powder is a promising approach. Even though the species are immiscible, an attritor mill has been successfully employed to create highly pre-milled powders, forcing Cu and Fe together as nano-features [13]. Milling parameters used in [6] will be taken as a starting point, as these have been successfully use to form nano-structured materials using HPT. Nonetheless, differences are expected between the two processes, therefore this paper expects an iterative process of powder milling and spraying.

U.C. Berkeley will form the powders using a Zoz GmbH Simoloyer attritor mill, while U. Wisconsin will perform the cold spray process. Successfully formed samples will be fully characterized as to mechanical properties before and after chemical treatment to confirm the development of a porous structure, and to optimize the cold spray process. The team intends to characterize the radiation resilience of the materials once the existence of a mechanically sound nanofoam is has been confirmed.

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