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Indentation creep behavior of cold sprayed aluminum amorphous/nano-crystalline coatings

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ABSTRACT

In this study, we report room temperature creep properties of cold sprayed aluminum amorphous/nanocrystalline coating using nanoindentation technique. Creep experiments were also performed on heat treated coatings to study the structural stability and its influence on the creep behavior. The peak load and holding time were varied from 1000 to 4000 μN and 0 to 240 s respectively. Stress exponent value (n) vary from 5.6 to 2.3 in as-sprayed (AS) coatings and 7.2–4.8 in heat treated (HT) coatings at peak load of 1000–4000 μN at 240 s hold time. Higher stress exponent value indicates heat treated coatings have more resistance to creep deformation than as-sprayed coatings. Relaxed, partially crystallized structure with less porosity, and stronger inter-splat boundaries restrict the deformation in heat treated coatings as compared to greater free volume generation in amorphous as-sprayed coatings. The computed activation volume of heat treated coatings is twice of as-sprayed coatings indicating greater number of atom participation in shear band formation in heat treated coatings. The proposed mechanism was found to be consistent with the stress exponent values.

1. Introduction

Bulk metallic glasses (BMG) exhibit unique mechanical properties and high potential for applications such as advanced structural and functional materials [1]. Due to their high-strength, high elastic limit and excellent corrosion resistance, BMGs have attracted increasing interest in the research community [2,3]. In particular, Aluminum based BMGs have excellent properties as compared to their crystalline counterparts [4–6]. Al-BMGs have exhibited high strength (above 1000 MPa, 3–4 times higher than crystalline counter parts), low density (3.2–3.7 g/cm^3) and better corrosion and wear properties [7–10]. Additionally, multi-components in Al amorphous alloys enhance the glass forming ability and super cooled liquid region to obtain the thick glassy structure components with relatively low cooling rates [10]. Further, the presence of nano α-Al (FCC) phase in the glass matrix of Al-BMGs increases strength up to 1500 MPa [11,12].

The use of nanoindentation for the creep characterization of bulk metallic glasses (BMGs) has increased in the past few years. In such tests, the sample may be prepared easily and only a small piece of the specimen is sufficient for accurate measurements, thus rendering this particular technique attractive and advantageous [13]. Nanoindentation creep studies have been carried out on most common La, Ce, Ti, Fe, Zr, Cu, Mg based BMGs [13–18]. The creep displacement has been observed in both low (La, Ce) and high (Fe, Zr) glass transition (T_g) BMGs in room temperature creep tests [13,16]. An increase in creep displacement with an increase in the peak hold load and loading rate at same peak load were reported [14,15,17–19]. In order to understand the creep behavior of BMGs, creep displacement as a function of hold period has been analyzed and stress exponent factor (n) has been computed. An increase in stress exponent factor (n) with an increase in the load and a decrease in 'n' with increase in strain rate was observed in Fe-BMGs [14,15,17]. However, an opposite trend was noticed in Cu-Zr BMGs [20]. Wang et al. reported strain rate sensitivity (m) which is reciprocal of stress exponent (n) of Zr-BMGs, becoming independent of loading strain rate when the indentation depth cross 50 nm [18]. Creep deformation mechanisms in BMGs were explained by theories like shear band formation (STZ) and free volume due non-crystalline nature of BMGs.

A very few studies have reported on creep behavior of as-cast and annealed bulk metallic glasses [20,21]. The creep of Cu-Zr and Zr BMGs is strongly affected by stress- relaxation/annealing. The annihilation of defects reduce the free volume in the Cu-Zr BMGs during annealing significantly influenced the creep properties of BMGs [20,21]. However, these studied are limited to cast BMGs in

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Cu molds.

In the present study, creep behavior of *cold sprayed Al based BMG coatings* has been reported. It is emphasized that novelty of this study stems from the fact that creep behavior of Al based BMG has never been studied. Moreover, the microstructure obtained by cold spraying is significantly different from cast BMG structure. In cold spray technique, feedstock in the powder form is accelerated to high velocity impact on the substrate and forms coating as a layered structure. Coating structure consists of weak splat boundaries, cracks and porosity which could influence the time dependent deformation behavior. In this study, thick Al-amorphous/nano-crystalline coatings are deposited on Al-6061 using cold spray technique. Coatings are heat treated just below the crystallization temperature. Creep properties of both as-sprayed and heat treated coatings are analyzed using nanoindentation technique at room temperature as a function of peak load and hold time. The results are interpreted in-terms of coating microstructure and properties.

2. Experimental details

2.1. Powder morphology and coating deposition

Aluminum amorphous/nanocrystalline powder having composition (Al-4.4Y-4.3Ni-0.9Co-0.35Sc (at%)) is deposited on Al-6061 substrate by cold spray technique. Aluminum amorphous alloy powder is obtained by gas atomization route. The powder has spherical morphology with size range from 2.5 to 45 μm with an average size of 11 μm. Coatings were deposited up to 250 μm thickness. These coatings are heat treated at 300 °C in order to study the structural stability and its influence on the properties of the coating. More details on the powder characteristics and coating deposition has been found in reports published by present authors [22,23].

2.2. Nanoindentation creep tests

All samples were polished to mirror smooth finish for creep studies. Nanoindentation tests are performed on mirror finished coating surfaces at room temperature using Hysitron TI 900 Triboindenter and a Berkovich tip. Tests are performed at peak loads of 1000, 2000 and 4000 μN. The time required to reach the peak load is fixed at 5 s. The holding time is varied at each peak loads to study the subsequent effect. The holding times are: 0, 5, 10, 20, 30, 60, 120 and 240 s. Ten tests were conducted for each condition for the sake of reproducibility of the data. Same procedure was repeated for the heat treated coatings and the data is recorded for further analysis and interpretation. The creep indentations are profiled after each test using scanning probe microscope (SPM) in TI 900 triboindenter to understand the indent morphology in as-sprayed and heat treated coatings.

3. Results and discussion

3.1. Coating structure and properties

Cross-sectional microstructure of cold sprayed Al amorphous alloy coatings in as-sprayed and heat treated conditions studied under SEM are shown in Fig. 1. Heat treated coating exhibited dense structure with less porosity (0.5%) due to solid state diffusion during heat treatment compared to as-sprayed coating (2%). XRD analysis (Fig. 2) reveals the presence of nano-crystalline α-Al FCC phase and intermetallic phases (Al_3Y, Al_3Sc, Al_4YNi and Al_9Co_2) in the heat treated coating against broadened peaks and nano-crystalline α-Al FCC phase peaks in as-sprayed coating. Hardness and modulus of coatings are measured using nanoindentation technique. Heat treated coatings exhibited slightly higher hardness of 5.25 GPa against 5 GPa in as-sprayed coatings.

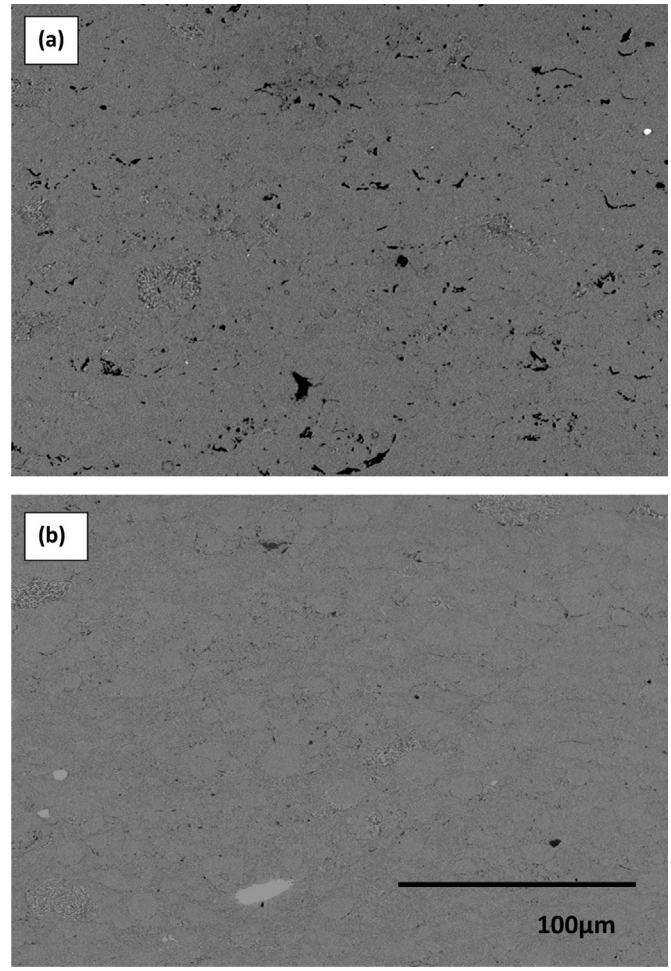

Fig. 1. Cross sectional SEM images of cold sprayed Al amorphous alloy coatings (a) as-sprayed (AS) and (b) heat treated (HT) conditions.

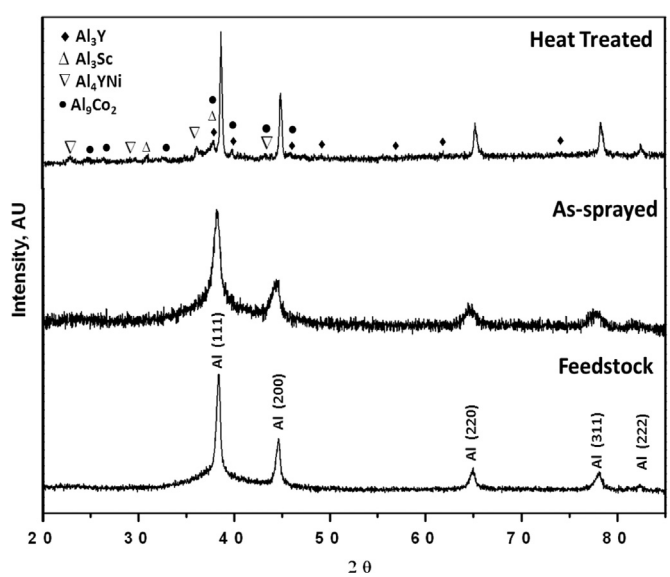

Fig. 2. X-ray diffraction patterns of initial powder feedstock, as-sprayed and heat treated (HT) Al amorphous coatings.