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Mechanical intermixing of elements and self-organization of (FeNi) and (CoFeNi) nanostructured composite layers on a Ti sheet under ball collisions

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ABSTRACT

A Ti sheet was subjected to intense plastic deformation through ball collisions initiated in a mechanically vibrated vial. The Ti was cut into a disk shape and fixed on one side of the vial with either Ni or Co disks fixed on the opposite side. The objective here was to intentionally use the Ni and Co disks as a source of Ni and Co impurities, while steel balls were to serve as a source for Fe impurities. During processing, ball collisions continuously introduced impurities from the grinding media onto the Ti surface, caused strong material flow, and induced mechanical intermixing of the elements, resulting in self-organization of the polycrystalline nanocomposite structure with an average grain size of about 8 nm. The phase composition of the alloyed layers was dependent on the material transferred into the system. When both Ti and Ni disks were subjected to ball collisions, the alloyed layer was composed of fcc (Fe,Ni) and Ti grains. However, when the Ni disk was subsequently replaced with Co, the layer consisted of bcc and fcc CoFeNi along with Ti grains. The fcc (Fe,Ni) phase was formed on the basis of the fcc Ni crystal structure, while the bcc Fe structure served as the basis for the bcc CoFeNi phase. The as-fabricated nanocomposite layers were extremely hard (~900 HV on the average), and a nearly three-fold increase was observed in the surface hardness of the Ti sheet after processing. The as-fabricated layers exhibited magnetic properties representative of soft-magnetic materials.

1. Introduction

Trends towards the miniaturization of industrial products impose new constraints on metallic materials. The demand for miniaturization is driven by developments in electronic devices, sensor technology, biotechnology, medical tools, aerospace technology, and mini- and micro-robotics [1,2]. Modern materials utilized in such applications should exhibit property profiles that satisfy specific mechanical, thermal, and electromagnetic requirements. However, multifunctional characteristics are difficult to achieve in conventional homogeneous alloys, and it is believed that existing industrial alloys have reached their performance limits [3–7]. Multifunctional property profiles could be easier to attain using multicomponent composite systems that combine different materials to form a hybrid structure with the best properties of each of its components [3–7]. Biological systems have recently been cited as an example of natural complex composites whose hierarchical structures have developed by self-organization and self-assembly [8]. Self-organization is a fundamental feature of natural systems and the manner by which materials are assembled from simple to more complex structures [8–10]. It has been suggested that natural self-organizing hierarchical structures could serve as prototype for the design of modern composite materials [3–10].

The development of lightweight, high-performance materials with multifunctional characteristics presents a challenging task. New synthesis routes should be devised for the production of such complex composite materials, as it is challenging to fabricate multicomponent systems with different physical and chemical properties by conventional high-temperature metallurgical

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processes. A potential alternate strategy for the synthesis of multicomponent systems may be the utilization of severe plastic deformation (SPD) techniques [11–13]. Traditionally, SPD methods were developed for grain refinement and the production of ultrafine-grained/nanocrystalline materials. Recently, it was demonstrated that SPD techniques induce unique phenomena in alloys, including strong material flow, mechanical intermixing of components on the atomic level, amorphization, non-equilibrium interdiffusion, and the formation of supersaturated solutions that may allow for the fabrication of nanocomposite materials [12,14–22]. The application of SPD methods to multicomponent systems could also lead to self-organization and the formation of complex patterns [14,23–25]. For example, it was reported that intense deformation applied to a multicomponent system caused the formation of a nanolaminated amorphous/crystalline composite structure [23]. The realization of such a structure could be attributed to a self-organization process involving local interactions between the components of an initially disordered system [8,26]. It appears that strong deformation-induced plastic flow in materials plays a key role in the formation of complex patterns. Previous studies have illustrated that materials may behave like a fluid under intense deformation, resulting in turbulence and swirling [14,22,23,27–29]. The chaotic motion of such plastic flow causes mechanical intermixing of the components and reactions between the elements. Consequently, the system undergoes changes from a simpler to a more complex structure via self-organization. Indeed, deformation-induced self-organization could be a sophisticated process that depends on the starting constituents and reactions between the elements. To gain a clearer understanding of the deformation-induced self-organization phenomenon, information on the intermixing of elements and the structural development from the atomic to microscopic level is needed. The mechanisms of elemental intermixing during SPD have not yet been fully explained, although several attempts have been made to describe how atoms may intermix in certain immiscible systems (e.g., defect-assisted diffusion, dislocation shuffle mechanisms, and shear-induced chemical mixing) [30–33]. Furthermore, Rigney et al. recently suggested that the local vorticity arising during plastic flow could be responsible for mechanical mixing [28,29]. New insights into the nature of atomic-level processes associated with microstructural development during intense deformation in different multicomponent systems will be of great help in both understanding the deformation-induced self-organization phenomenon and designing new complex composite alloys.

In the present work, Ni, Fe, and Co impurities were deliberately introduced onto the surface of Ti via ball collisions from grinding media in order to study the deformation-induced intermixing of elements and fabricate a multicomponent composite structure. As will be demonstrated herein, the intense intermixing of elements due to ball collisions results in the formation of complex patterns whose development depends on the initial constituents introduced into the system during processing. The devised technique can be effectively used for the fabrication of thick, soft-magnetic nanocomposite layers on metallic sheets. At present, many soft-magnetic materials are produced by traditional powder compaction techniques [34]. Such routes comprise several technological operations, including powder manufacturing, powder blending, compacting, and sintering. However, the sintering and heat treatment steps lead to grain growth and coarsening of the structure. The proposed technique allows for the fabrication of thick soft-magnetic nanocomposite layers directly on a surface in a single operation without the need for a special atmosphere or elevated temperature. In addition, the as-fabricated layers may be utilized as electromagnetic wave absorbers [35–38], while the Co and Ni constituents serve to improve the wear, heat, and corrosion resistances of the workpiece [39–41]. The resulting lightweight structure can exhibit enhanced mechanical, thermal, and electromagnetic characteristics and may thus be attractive for use in aerospace applications.

2. Experimental details

Ti (99%), Ni (99%), and Co (99%) sheets with a thickness of 3 mm (Nilaco Corp., Japan) were used in the present experiments. Disks with diameters of 50 mm were cut from the as-received sheets. For the treatment process, a vibration vial composed of SKD 11 steel (tool steel: Fe-1.5C–1Mo–12Cr-0.35 V wt%) was designed; a schematic of the vial is shown in Fig. 1a. A Ti disk was fixed on one side of the vial, while Ni or Co disks were attached on the opposite side. Eighty grams of steel balls, each with a diameter of 7 mm, were loaded into the vial to produce the desired impacts. The vial was sealed inside an argon glove box using silicone rubber “O” rings so as to prevent exposure to the outside atmosphere and ensure that interstitial contaminants are kept to a minimum during the milling [42]. Mechanical vibration of the vial was carried out with a Spex high-energy mill (8000D-230 Mixer/Mill). One of the main problems associated with ball treatment methods is that impurities are introduced into the material as a result of contamination from the milling media [22,23,42]. However, the objective here was to intentionally use Ni and Co disks as a source of Ni and Co impurities, while steel balls are utilized as a source of Fe impurities. Mechanical vibration of the vial generated ball impacts against both sides of the vial. With each swing of the vial, the balls collide with either the Ti or Ni (or Co) disks, as shown in Fig. 1a. When the balls impacted the Ti disk, fragments of impurities from the balls were transferred onto the Ti surface. This occurs as the two deformable surfaces are pressed together and come into intimate contact [22,43]. When the surfaces separate, pieces from the balls adhered to the Ti surface, thereby allowing for intermixing of the components. In this study, a Ti disk was treated along with Ni for 2 h. In addition, a Ti disk was treated along with Ni for 1 h, at which point the Ni disc was replaced with Co. The Ni-processed Ti and the Co disk were then subjected to 1 h of ball milling.

The structures of the as-fabricated specimens were studied by X-ray diffraction (XRD) analysis using a Rigaku diffractometer with CoKα radiation. Cross-sections for microstructural observation were prepared with a JEOL SM-09010 cross-section polisher. A field-emission scanning electron microscope (SEM: JEOL JSM-7000F) equipped with an energy dispersive spectroscopy (EDS) detector (Oxford Instruments) was utilized to evaluate the microstructure and composition of the samples. Specimens for transmission electron microscopy (TEM) analysis were prepared on molybdenum TEM grids using a focused ion bean instrument (FIB: FEI Helios NanoLab DualBeam). The specimen structure and chemical composition were also studied with an atomic-resolution analytical electron microscope (JEOL JEM-ARM200F) operated at 200 kV and equipped with a Quantax (Bruker) energy-dispersive X-ray spectroscopy microanalysis system. EDS maps, in which a complete spectrum was stored for every pixel, were acquired in scanning TEM (STEM) mode with a probe size of 0.2 nm. Quantax processing tools were employed to extract, quantify, and compare the EDS spectra acquired for selected regions of the map. All TEM and SEM images shown in this paper are cross-sectional images.

The microhardness was measured using an automated load Mitutoyo hardness testing machine. The surface microhardness of the processed Ti sheet was measured with load of 500 g applied for 10 s, while the microhardness of the as-fabricated composite layer was evaluated from the cross-section with load of 10 g applied for 10 s. The cross-sections for microhardness testing were prepared with a JEOL SM-09010 cross-section polisher. In order to ascertain