Laser Cladding of Quasi-Crystal-Forming Al-Cu-Fe-Bi on an Al-Si Alloy Substrate

KRISHANU BISWAS, ROLF GALUN, BARRY L. MORDIKE, and KAMANIO CHATTOPADHYAY

We report here the results of an investigation aimed at producing coatings containing phases closely related to the quasi-crystalline phase with dispersions of soft Bi particles using an Al-Cu-Fe-Bi elemental powder mixture on Al-10.5 at. pct Si substrates. A two-step process of cladding followed by remelting is used to fine-tune the alloying, phase distribution, and microstructure. A powder mix of $Al_{64}Cu_{22.3}Fe_{11.7}Bi_2$ has been used to form the clads. The basic reason for choosing Bi lies in the fact that it is immiscible with each of the constituent elements. Therefore, it is expected that Bi will solidify in the form of dispersoids during the rapid solidification. A detailed microstructural analysis has been carried out by using the backscattered imaging mode in a scanning electron microscope (SEM) and transmission electron microscope (TEM). The microstructural features are described in terms of layers of different phases. Contrary to our expectation, the quasi-crystalline phase could not form on the Al-Si substrate. The bottom of the clad and remelted layers shows the regrowth of aluminum. The formation of phases such as blocky hexagonal Al-Fe-Si and a ternary eutectic (Al + $CuAl_2$ + Si) have been found in this layer. The middle layer shows the formation of long plate-shaped $Al_{13}Fe_4$ along with hexagonal Al-Fe-Si phase growing at the periphery of the former. The formation of metastable Al-Al_6Fe eutectic has also been found in this layer. The top layer, in the case of the as-clad track, shows the presence of plate-shaped $Al_{13}Fe_4$ along with a 1/1 cubic rational approximant of a quasi-crystal. The top layer of the remelted track shows the presence of a significant amount of a 1/1 cubic rational approximant. In addition, the as-clad and remelted microstructures show a fine-scale dispersion of Bi particles of different sizes formed during monotectic solidification. The remelting is found to have a strong effect on the size and distribution of Bi particles. The dry-sliding wear properties of the samples show the improvement of wear properties for Bi-containing clads. The best tribological properties are observed in the as-clad state, and remelting deteriorates the wear properties. The low coefficient of friction of the as-clad and remelted track is due to the presence of approximant phases. There is evidence of severe subsurface deformation during the wear process leading to cracking of hard phases and a change in the size and shape of soft Bi particles. Using these observations, we have rationalized possible wear mechanisms in the Bi-containing surface-alloyed layers.

I. INTRODUCTION

QUASI-CRYSTALLINE materials were discovered in 1984 by Dan Shectmann *et al.*[1] to herald a new era in crystallography and atomic architecture of solids. A few years after the rush of the initial discovery, a few laboratories started looking at the properties of these materials and, thereby, exploring the possibility of the potential use of these materials. Quasi-crystalline materials are characterized by the long-range order without translational periodicity featuring noncrystallographic symmetry. The aperiodic arrangement of atoms in the lattice leads to several distinctive properties, such as very high hardness,[2] low friction coefficient,[3] low thermal conductivity,[4] low surface energy,[5] high corrosion and oxidation resistance,[6] *etc*. These properties make them potentially useful in many applications. However, due to their low room-temperature ductility,[7] these materials are often not found suitable for bulk applications. An attractive alternative is to use these materials in the form of coatings on soft metals and alloys, such as aluminum and Al-Si alloys.

The Al-Cu-Fe system is known to be a stable quasicrystal-forming system.[8] This ternary system has been extensively studied due to the possibility of a number of applications in the form of coatings.[9] However, their brittleness at room temperature and complex solidification pathways have made it difficult to use them. Therefore, it is important to study the effect of the addition of other elements on the morphological modifications of icosahedral phase– forming Al-Cu-Fe alloys. The quaternary addition of Si to this system significantly influences the phase formation. According to Lee *et al.*,[10] an Si addition up to 5 at. pct leads to an increase of the volume fraction of icosahedral phase in the microstructure. A further increase of Si content from 9 at. pct to 15 at. pct leads to the formation of the 1/1 cubic rational approximant to the icosahedral phase. These approximant phases are crystalline in nature with quasi-crystalline motifs and can be derived from the rational cut of six-dimensional hyperspace of the icosahedral quasi-crystals. Therefore, they have similar properties to those of the parent quasi-crystalline phases. According to Quivy *et al.*,[11] the cubic rational approximant phase exists over a large domain of compositions and temperatures, sometimes in coexistence with the

KRISHANU BISWAS, Graduate Student, and KAMANIO CHATTOPADHYAY, Professor, are with the Department of Metallurgy, Indian Institute of Science, Bangalore-560012, India. Contact e-mail: kamanio@met.iisc.ernet.com ROLF GALUN, Scientist, and BARRY L. MORDIKE, Emeritus Professor, are with IWW, Technical University, Clausthal, D-38678, Clausthal-Zellerfeld, Germany.
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