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Build direction dependence of microstructure and high-temperature tensile property of Co–Cr–Mo alloy fabricated by electron beam melting

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Abstract

The microstructures and high-temperature tensile properties of a Co–28Cr–6Mo–0.23C–0.17N alloy fabricated by electron beam melting (EBM) with cylindrical axes deviating from the build direction by 0°, 45°, 55° and 90° were investigated. The preferred crystal orientations of the γ phase in the as-EBM-built samples with angles of 0°, 45°, 55° and 90° were near [0 0 1], [1 1 0], [1 1 1] and [1 0 0], respectively. $M_{23}C_6$ precipitates ($M = $ Cr, Mo or Si) were observed to align along the build direction with intervals of around 3 μm. The phase was completely transformed into a single ε-hexagonal close-packed (hcp) phase after aging treatment at 800 °C for 24 h, when lamellar colonies of M_2N precipitates and the ε-hcp phase appeared in the matrix. Among the samples, the one built with 55° deviation had the highest ultimate tensile strength of 806 MPa at 700 °C. The relationship between the microstructure and the build direction dependence of mechanical properties suggested that the conditions of heat treatment to homogenize the microstructure throughout the height of the EBM-built object should be determined by taking into account the thermal history during the post-melt period of the EBM process, especially when the solid–solid transformation is sluggish.

Keywords: Cobalt chromium alloys; Powder processing; Tensile behavior; Phase transformation; Texture

1. Introduction

Cobalt-based alloys have been widely used as materials for valve seats in nuclear power plants, aerospace fuel nozzles and engine vanes, as well as orthopedic and dental implant materials, because of their strength at high temperature, corrosion resistance, excellent wear resistance and biocompatibility [1–5].

The strengthening mechanisms of cobalt-based alloys include solid-solution strengthening, secondary-phase strengthening and grain-refinement strengthening [1]. Solid-solution strengthening is generally attributed to the increase in frictional stress for dislocation motion resulting from the solute–dislocation interaction. Secondary-phase strengthening in cobalt-based alloys is mostly due to carbides. The carbides usually consist of carbon and one or more metal elements (M) of chromium, molybdenum, tungsten, niobium, tantalum, zirconium, vanadium and titanium. Their reported forms include MC, M_6C, M_7C_3, $M_{23}C_6$ and occasionally M_2C_3 [1,2,6–9]. Nitrides may have a positive effect as TiN, HfN and NbN in superalloys [7], although they are expected to be less effective for strengthening owing to their lower thermodynamical stability than that of carbides, which causes degeneration reactions during service [6]. It has been also reported that CrN or Cr_2N is formed, depending on the temperature and N content, during the casting and forging of Co–Cr–Mo

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alloys [10]. In addition, the strength of a Co–Cr–Mo alloy is known to depend significantly on its microstructure, which consists of the γ-face-centered cubic (fcc) phase, which is stable at high temperatures, the ε-hexagonal close-packed (hcp) phase, which is stable at lower temperatures, or both phases [11–13]. Since the γ-fcc phase can exist as a metastable phase even at low temperatures, where the ε-hcp phase is stable in equilibrium, a variety of microstructures can be formed depending on the thermal history. For example, the γ-fcc phase can be a secondary phase for the ε-hcp phase matrix and vice versa. Even in a single phase, various grain structures can be formed as a result of γ-to-ε or γ-to-ε phase transformation. Moreover, Cr_2N has been reported to contribute to grain-refinement strengthening of the biomedical Co–27Cr–5Mo–0.16N alloy by reverse transformation [12].

Carbide precipitates located at both grain boundaries and within the grains are expected to increase the strengthening effect [1]. The precipitates at the grain boundaries prevent sliding and migration of the boundaries, and a skeletal network of precipitates can support some of the imposed stress to some extent. Intragranular precipitation strengthens the matrix by providing obstacles to the movement of dislocations and thus inhibiting crystallographic slip. In the casting of carbon-containing alloys, the distribution of carbides is determined by the pouring temperature of the melt, the cooling rate and the heat-treatment conditions.

Directional solidification can create aligned grain structures, grain boundaries and even strengthening filaments. It was demonstrated that the DZ40M cobalt-based alloy with a columnar grain structure oriented to the $\langle 001 \rangle$ direction, which was fabricated by directional solidification, has increased rupture strength and resistance against thermal fatigue [8], features that are mainly attributed to carbides. The columnar grain matrix with preferential orientation is believed to contribute to considerable improvement in ductility. Because unidirectional heat extraction also exists in electron beam melting (EBM), the grains are expected to be oriented in the $\langle 001 \rangle$ direction. By changing the angle between the cylinder axis and the build direction, different preferentially oriented rods are obtained, and the carbide array direction forms a particular angle with the cylinder axis. This will bring about excellent mechanical strength in the cylinder axis direction of the rod by controlling the deviation angle.

Recently, EBM has become an established process for additive manufacturing that can create three-dimensional (3-D) complex structures from precursor metal powders [14–19]. In the EBM process, a high-power electron beam is scanned to melt metal powder selectively along a series of 2-D slices of a 3-D object repeatedly, layer by layer. When the EBM was applied to Co–26Cr–6Mo–0.2C alloys [15,20], the $M_{23}C_6$ carbides were found to align along the build direction (Z axis) within grains owing to unidirectional heat flow. The ultimate tensile strength (UTS) of the as-EBM-built sample was higher than that of as-cast or wrought ASTM F75 Co–Cr–Mo alloys [15]. However, the microstructures of the Co–26Cr–6Mo–0.2C alloys fabricated by EBM have been observed by optical microscopy only to examine the carbide array and by transmission electron microscopy (TEM) for relatively local, lattice-defect structures. As mentioned above, the phase constitution and grain structures, including the crystal orientation distribution (i.e. texture), should also be examined in order to understand the relationship between the microstructural and mechanical properties.

In this study, Co–Cr–Mo alloy rods containing high amounts of carbon and nitrogen were fabricated by EBM. The high-temperature tensile properties of the rods with various orientations were investigated, with special focus on the effects of anisotropic columnar grain structure and carbide distribution.

2. Experimental

The samples were fabricated on an Arcam A2 EBM system (Arcam AB, Mölndal, Sweden). The powder used in the experiment consisted of spherical particles and attached small satellite particles, with an average particle size of 64 μm. The chemical composition of the Co–28Cr–6Mo–0.23C–0.17N alloy powder, shown in Table 1, was within the range of ASTM F75 standards. Relatively higher carbon and nitrogen contents were selected in order to obtain a large amount of precipitates and to stabilize the γ-fcc phase, which allowed the γ-fcc crystal growth with $\langle 001 \rangle$ orientation. The cylindrical axes deviating from the build direction (Z axis) by 0°, 45°, 55° and 90°, shown in Fig. 1, were chosen to orient the cylindrical axes to the [001], [110], [111] and [100] directions, respectively. Hereafter, the Co–28Cr–6Mo–0.23C–0.17N alloy rods fabricated in the directions of 0°, 45°, 55° and 90° from the Z axis are designated as the 0°-sample, 45°-sample, etc. The rods were 15 mm in diameter and 85 mm in height. The samples were held at 800 °C for 24 h to transform them all into the ε-hcp phase. The tensile samples were taken from the top part of the as-EBM-built samples and cut so that the tensile direction was parallel to the cylinder axis. The gauge part was rectangular, measuring 11 mm in length and 2 mm in width, with a thickness of 1 mm. Tensile tests were conducted at 700 °C with a strain rate of $1.5 \times 10^{-4}\ s^{-1}$ on an Instron 8562 testing machine. In order to examine the effect of the matrix phase on the high-temperature tensile properties, the tensile test was conducted on the single-γ-phased 90°-sample. This sample was formed by skipping the post-EBM aging heat treatment because it required a relatively low build height of 15 mm, which allowed us to avoid the γ-to-ε transition during the EBM process. The microstructures were investigated by scanning electron microscopy (SEM), electron backscatter

Table 1
Chemical composition (wt.%) of the alloy used in the EBM process.

Co	Cr	Mo	Ni	Si	Mn	C	N	O
Bal.	28.4	6.66	0.18	0.45	0.69	0.23	0.20	0.023