On the Decomposition of $\beta$ Phase in Some Rapidly Quenched Titanium-Eutectoid Alloys

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The decomposition of the $\beta$ phase in rapidly quenched Ti-2.8 at. pct Co, Ti-5.4 at. pct Ni, Ti-4.5 at. pct, and 5.5 at. pct Cu alloys has been investigated by electron microscopy. During rapid quenching, two competitive phase transformations, namely martensitic and eutectoid transformation, have occurred, and the region of eutectoid transformation is extended due to the high cooling rates involved. The $\beta$ phase decomposed into nonlamellar eutectoid product (bainite) having a globular morphology in Ti-2.8 pct Co and Ti-4.5 pct Cu (hypoeutectoid) alloys. In the near-eutectoid Ti-5.5 pct Cu alloy, the decomposition occurred by a lamellar (pearlite) type, whereas in Ti-5.4 pct Ni (hypereutectoid), both morphologies were observed. The interfaces between the proeutectoid $\alpha$ and the intermetallic compound in the nonlamellar type as well as between the proeutectoid $\alpha$ and the pearlite were often found to be partially coherent. These findings are in agreement with the Lee and Aaronson model proposed recently for the evolution of bainite and pearlite structures during the solid-state transformations of some titanium-eutectoid alloys. The evolution of the Ti$_2$Cu phase during rapid quenching involved the formation of a metastable phase closely related to an $\alpha$-type phase before the equilibrium phase formed. Further, the lamellar intermetallic compound Ti$_2$Cu was found to evolve by a sympathetic nucleation process. Evidence is established for the sympathetic nucleation of the proeutectoid $\alpha$ crystals formed during rapid quenching.

I. INTRODUCTION

Several studies have been carried out recently on rapid solidification (RS) of titanium alloys that included a number of conventional alloys\cite{1,2} and novel titanium alloys with additions of rare earth oxides like erbia, yttria, lanthanum oxide, etc., and metalloids like C and B.\cite{5} Attempts were also made to study the effect of RS on the ductility of titanium aluminides.\cite{6,7,8} Titanium-eutectoid alloys form a class that can be strengthened by precipitation of the intermetallic phase. However, earlier attempts at the development of these alloys through ingot metallurgy have been hampered due to the segregation of the solute elements. Hence, several research workers made attempts to circumvent the segregation problem through RS.\cite{9,10} A survey\cite{11,12} of the literature indicates that very few attempts were made to understand the mechanism of eutectoid decomposition in these alloys. Such studies assume still greater significance because of the fact that the results observed in titanium alloys are at variance with those for analogous Fe-C alloys. In a study conducted on the solid-state eutectoid decomposition in titanium-X (where X = Bi, Co, Cr, Cu, Fe, Mn, Ni, Pb, Pd, and Pt) alloys, Franti et al.\cite{13} concluded that alloys of hypoeutectoid composition decomposed predominantly by a nonlamellar (bainite) mode except in the case of Ti-Cu, where the $\beta$ phase decomposed by both lamellar (pearlite) and nonlamellar modes. In the case of near-eutectoid alloys, the decomposition mode seems to be predominantly pearlitic or lamellar.

These findings were mainly based on optical microscopy. It was suggested that the interfacial structures might play a significant role in the transformation mechanisms. Lee and Aaronson\cite{14,15} and Lee et al.\cite{16} carried out detailed studies on the mechanisms of lamellar and nonlamellar eutectoid decomposition in several titanium-eutectoid alloys by solid-state reactions. These studies have emphasized the importance of the ledge-height-to-ledge-spacing ratio at the intermetallic-compound/$\beta$-phase interface in dictating the mode of eutectoid decomposition. Proeutectoid $\alpha$ nucleation and intermetallic compound nucleation at the $\alpha$/$\beta$ interfaces seem to depend very much on the semicoherent nature of the boundaries. Furuhara et al.\cite{17} have very elegantly brought out the importance of partially coherent boundaries in proeutectoid $\alpha$ and eutectoid reactions in titanium alloys.

In the present study, an attempt has been made to understand the eutectoid decomposition in the rapidly solidified titanium-eutectoid alloys in light of the results obtained from the solid-state transformations by Aaronson and his co-workers.\cite{14,15,16} The phase diagrams of the systems chosen are given in Figure 1.\cite{18}

II. EXPERIMENTAL PROCEDURE

The primary melting of the titanium alloys was carried out by the nonconsumable vacuum arc-melting technique at Defence Metallurgical Research Laboratory (Hyderabad, India). Fifty-gram buttons of each alloy were melted under an argon atmosphere. Binary alloys of Ti-Co, Ti-Ni, and Ti-Cu were melted, starting with titanium sponge and high-purity solute elements. The buttons were melted four to five times to achieve homogenization. These buttons were cut into small pellets of 5 g for further RS experiments. Rapid solidification was carried out by the electron-beam melting and
splat-quenching technique. The details of the technique are described elsewhere.\textsuperscript{[10,19]} Sixty-μm-thick ribbons were obtained by this process, and these were used in the study. The compositions of the ribbons as determined by energy-dispersive spectroscopy using a semiquantitative analysis program are as follows: Ti-2.8 at. pct Co, Ti-5.4 at. pct Ni, Ti-4.5 at. pct Cu, and Ti-5.5 at. pct Cu. Thin foils for transmission electron microscopy (TEM) studies were prepared in a Tenupol twin-jet electropolishing unit using an electrolyte of methanol and nitric acid mixture (60 pct:40 pct) at -50 °C and a DC potential of 40 V. X-ray diffractograms were recorded in a PHILIPS\textsuperscript{*} diffractometer using Cu Kα radiation.

### III. RESULTS

#### A. Proeutectoid α Nucleation in Rapidly Quenched Ti-2.8 At. Pct Co and Ti-4.5 At. Pct Cu Hypoeutectoid Alloys

X-ray diffraction results from Ti-2.8 pct Co alloy indicated the presence of hexagonal close-packed (hcp) (α) and body-centered cubic [retained β-Ti(Co)], with a lattice parameter of $a = 0.32$ nm] phases. In Ti-4.5 pct Cu alloy, only an hcp phase was found. The volume fraction of Ti2Co and Ti2Cu formed on eutectoid decomposition was below the detection limit by X-ray diffraction. Scanning electron microscopic observations revealed grain boundary allotriomorphs, Widmanstätten plates, and side plates (Figure 2). The nature of evolution of these phases is further understood from the transmission electron microscopic studies on Ti-2.8 pct Co (Figure 3). Here β is retained as a thick layer between parallel plates of proeutectoid α phase or as a boundary layer surrounding

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Fig. 1 — (a), through (c) Phase diagrams of titanium-cobalt, titanium-nickel, and titanium-copper systems according to Murray.\textsuperscript{[10]}

Fig. 2 — Scanning electron micrograph of rapidly solidified Ti-2.8 pct Co alloy. Side plates and grain boundary allotriomorphs are seen.