Transformations in $\alpha_2 + \gamma$ Titanium Aluminide Alloys Containing Molybdenum: Part II. Heat Treatment

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The response of as-cast structures of 12 alloys in the Ti-Al-Mo system containing 44 to 50 at. pct Al and 2 to 6 at. pct Mo to simple single step heat treatments in the temperature range 1373 to 1673 K is described. The microsegregation patterns present in the cast structure persist to a large extent after heat treatment, especially below 1673 K. However, tentative conclusions regarding phase equilibria in this temperature and composition range are drawn from the results. High-temperature equilibria are dominated by the $\beta$, $\alpha + \beta$, and $\alpha + \gamma$ phase fields, while the $\beta + \gamma$ phase field dominates equilibrium below 1473 K. Three major types of transformation behavior are observed: a massive $\alpha$ to $\gamma$ transformation, which occurs within the $\alpha$ phase on quenching from 1673 and 1573 K in alloys centered around the 48 pct Al composition; a eutectoid transformation from $\alpha$ to $B2 + \gamma$ mixtures, which occurs at 1473 K and below in alloys centered around the 48Al-4Mo and 46Al-6Mo compositions; direct $\gamma$ precipitation in $\beta$, which occurs primarily in the 44Al-6Mo composition at 1273 K and below; and finally growth of $\gamma$ lamellae in $\alpha + \gamma$ lamellar structures with $B2$ precipitation on lamellar interfaces, which occurs over a broad range of alloy compositions and temperatures.

I. INTRODUCTION

We have initiated a study of alloys based upon TiAl with multiphase structures containing the $\gamma$, $\alpha_2$, and $\beta(B2)$ phases. Part I of this series of articles\(^{(1)}\) describes solidification structures of alloys containing 44 to 50 at. pct Al and 2 to 6 at. pct Mo. The effect of single step heat treatments at temperatures ranging from 1373 to 1673 K on the response of the as-cast structures is described in this part. This study has been carried out in order to assess the structures that might exist prior to hot working of such alloys, the degree of homogenization that is possible within relatively short heat treatment times, and the manner in which the microsegregated cast structures approach equilibrium. The study also provides an indication of phase equilibria in such alloys over this temperature range.

II. EXPERIMENTAL

The alloys listed in Part I of this series were heat treated at 1673, 1573, 1473, and 1373 K for 1, 2, 4, and 6 hours, respectively, and water quenched. Microstructures were characterized by scanning electron microscopy using back-scattered electrons (BSE) to highlight phase and composition contrast, and compositions of individual phases were determined by electron probe microanalysis (EPMA), as described in Part I. Transmission electron microscopy (TEM) was used to elucidate further details of structure, and X-ray diffraction (XRD) was used to confirm the phases present.

III. RESULTS

Figures 1 and 2 show low magnification micrographs of typical alloys containing 50 and 48 at. pct Al heat treated at various temperatures. The microstructures indicate that the extensive microsegregation present in these alloys in the cast structures (Part I) determines the evolution of structure on heat treatment to a large degree, since the dendritic patterns present in the cast structures are preserved on heat treatment. The alloys containing 46 and 44 at. pct Al solidify into the single-phase $\beta$ field and are not segregated to such a large extent (Part I); they are not shown at low magnification. Figures 3 through 6 show high magnification BSE micrographs of all the alloys, each figure representing a specific Al composition, as a function of heat treatment temperature and Mo level. These micrographs are taken so as to straddle an area ranging from the dendritic core to the interdendritic regions. Figure 7 shows TEM elucidating details of structure for some combinations of alloy and heat treatment. A typical XRD pattern showing peaks from the relevant phases, $\alpha_2$, $B2$, and $\gamma$, is given in Figure 8. Table I indicates the phase identified at each heat treatment temperature for all compositions by XRD, while Table II provides the chemistry of the individual phases for different alloys and heat treatments, where the microstructure is coarse enough to permit their measurement by EPMA. The subsequent description follows the same pattern as in Part I in that it considers the microstructure as a function of Mo concentration and heat treatment for each Al level in turn.

A. Alloys with 50 At. Pct Al (Figures 1 and 3)

The 50Al-2Mo alloy shows little variation from the cast structure on heat treatment at 1673 K, except that the $\gamma$ phases in the interdendritic regions (marked $1\gamma$) lose their continuity and are present as islands, while the primary $\alpha$ dendrites in similar orientations conglomerate to form roughly equiaxed grains (Figures 1(a) and 3(a)). It is assumed that the $\gamma$ lamellae within these grains (marked $L\alpha_2 + \gamma$) were not present at the heat treatment temperature but formed during the quench, since no coarsening of these lamellae were observed on heat treatment (compare Figures 3(a) and 3(c) of Part I). With decreasing heat treatment...
temperature in this alloy, both the interdendritic $\gamma$ and $\gamma$ lamellae grow at the expense of $\alpha$, such that at 1473 and 1373 K, largely equiaxed $\gamma$ grains are seen in the BSE micrographs (Figures 3(d), (g), and (j)). Transmission electron microscopy (Figure 7(a)) indicates that the grains originally containing $\alpha$ and $\gamma$ lamellae now contain lamellar boundaries of the $\gamma$ phase (marked $L\gamma$ in Figure 3) due to the dissolution of the intervening $\alpha$ phase. In addition, $\beta$ phase precipitates at these lamellar boundaries at these temperatures. Some $\alpha$ continues to be present, although distributed very heterogeneously in the Al lean regions. The phases identified at each temperature by XRD (Table I) are consistent with this description.

The cast structure of the 50Al-4Mo and 50Al-6Mo alloys contains the $\beta$ phase at the dendrite cores and $\gamma$ phase in the interdendritic regions (Part I). The response of these alloys to heat treatment is broadly similar. The $\beta$ phase of both alloys dissolves at 1673 K. The lamellar grains are replaced by finer equiaxed grains (marked $M\gamma$) in the area corresponding to the dendrite cores, while $\alpha$ lamellae thicken at the expense of $\gamma$ in the Al lean regions adjacent to the interdendritic $\gamma$ (Figures 3(b) and (c)). The equiaxed grain structure ($M\gamma$) extends almost to the boundary of the interdendritic $\gamma$ in the 50AI-6Mo alloy, and the volume fraction of interdendritic $\gamma$ decreases with increasing Mo, so that it is almost negligible in the 50AI-6Mo alloy (Figure 1(b)). Figures 7(b) and (c) show details of the $M\gamma$ structure, which consists of fine $\gamma$ grains with a high density of dislocations and stacking faults. A band of $\alpha$ and $\gamma$ lamellae is almost invariably present within clusters of such grains (Figure 7(b)). On heat treatment at 1573 K, a clear diffusion zone of lighter contrast, indicating a higher Mo level, is formed around dendritic cores (Figures 3(e) and (f)). The $\alpha$ lamellae dissolve in the Mo enriched region. In addition, precipitation of $\alpha$ plates is observed within the interdendritic $\gamma$ islands. X-ray diffraction indicates that all three phase are present in both the alloys at 1573 K. At lower heat treatment temperatures (Figures 3(h), (i), (k), and (l), B2 precipitation occurs along the lamellar boundaries in the Mo rich regions, while the $\alpha$ lamellae dissolve (marked $L\beta_2\gamma$) in the 50AI-6Mo alloy. A eutectoid reaction to $\beta_2 + \gamma$ also occurs at 1473 and 1373 K in the 50AI-6Mo alloy (marked $E\beta_2 + \gamma$). The $\beta$ phase in the dendrite cores is retained in both alloys. X-ray diffraction indicates that only $\beta_2$ and $\gamma$ phases are present at 1473 and 1373 K in all the alloys with 50 at. pct Al.

The chemistry values of the interdendritic $\gamma$ and $M\gamma$ have