1. INTRODUCTION

Powder metallurgy (P/M) approaches can lead to substantial departures from equilibrium ("far from equilibrium" processing) allowing novel combinations of constitutional and microstructural effects to be achieved [1, 2]. This in turn can lead to significant enhancements in mechanical and physical behavior compared to material produced by the more conventional ingot metallurgy (I/M) technique.

However, inherent to the P/M approach is the necessity to compact the powder produced into a solid article allowing use in device or structural components. To accomplish this consolidation step a thermal excursion is required. However, the material processed by "far from equilibrium" techniques can suffer a loss in the novel constitutional and microstructural effects: the magnitude of the loss being directly related to the extent of the thermal exposure [3]. In general, as the time-temperature exposure increases, the desirable features built-in to the material by the "far from equilibrium" process are removed (Fig. 1) [4]; recognizing that if these features are modified in a controlled fashion they can still give novel characteristics and enhanced behavior in the compacted article.

Nanostructured materials are materials with at least one dimension in the nanometer range (1 nm=10^-9 m), generally ≤100 nm. Because of their novel combinations of mechanical, physical, and magnetic properties they have received considerable attention in the past few years [5-10]. Nanostructured materials can be one-dimensional (layered), two-dimensional (fibrous) or three-dimensional (crystallites) [6]. However, the vast majority of work to date has been on the third type which is generally produced using a P/M approach; and this paper will only consider this type of nanostructured material.

Nanostructures in pure titanium and titanium terminal alloys have generally been produced by deformation methods such as mechanical alloying (MA) [11]. The grain size of MA material decreases exponentially with milling time and reaches a minimum value, after only a few hours of milling. Fig. 2 shows a plot of crystal size as a function of milling time for several titanium-aluminum alloys [12].

In an attempt to retain nanocrystals in MA'd Ti-24Al-11Nb (at.%) consolidation was conducted using dynamic explosive techniques [13]. The compacts produced exhibited less than 100% density, with the presence of intra- and interparticle porosity. When very high consolidation pressures were used, by increasing the impact velocity using a larger amount of explosive charge, evidence of melt pores was detected. A detailed evaluation of the microstructure revealed that this technique retained small nanocrystals about 15 nm in diameter. Thus while the goal of retaining the nanocrystals was achieved, less than a fully dense compact was obtained.

In the present work a study was made of the feasibility of retaining nanocrystals in TiAl compositions using HIP compaction, while obtaining a 100% dense com-
Fig. 1. Effect of time-temperature exposure on non-equilibrium material.

Fig. 2. Variation of crystal size as a function of milling time in mechanically alloyed Ti-Al (gamma) alloys.

Fig. 3. X-ray diffraction patterns of the Ti-55Al powder mixture (a) milled in an attritor to the amorphous phase, and (b) after HIPing at 975°C/207MPa/2h showing that the amorphous phase has crystallized to a mixture of γ-TiAl and α2-Ti3Al phases.

Table 1. Summary of results on HIP consolidated mechanically alloyed Ti-55at.%Al powder

<table>
<thead>
<tr>
<th>Consolidation method</th>
<th>Consolidation parameters (Temp(°C)/Press(MPa)/Time(h))</th>
<th>Grain size, by TEM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Milled</td>
<td></td>
<td>Amorphous</td>
</tr>
<tr>
<td>HIP</td>
<td>800/207/2</td>
<td>8-90</td>
</tr>
<tr>
<td>HIP</td>
<td>900/207/2</td>
<td>30-140</td>
</tr>
<tr>
<td>HIP</td>
<td>975/207/2</td>
<td>85 TiAl</td>
</tr>
<tr>
<td></td>
<td></td>
<td>220 Ti3Al</td>
</tr>
</tbody>
</table>

2. HOT ISOSTATIC PRESSING OF NANO-STRUCTURED GAMMA TiAl

Gamma TiAl powder, produced by gas atomization, with a conventional grain size requires a HIP temperature in excess of 1100°C to achieve full density [14]. In the present work two gamma TiAl compositions were investigated Ti-55Al(at.%) and Ti-47.5Al-3Cr(at.%) using both gas atomized and mechanically alloyed powder as starting stock.

2.1. Ti-55Al(at.%) alloy

Blended elemental Ti-55 at%Al powder was MA'd in a Szegvari 01-HD attritor for 115h under an argon atmosphere cover using a ball-to-powder weight ratio of 20:1. After MA the powder was in an amorphous state as demonstrated by the broad peak in the X-ray diffraction pattern, Fig. 3. This material was compacted using the HIP parameters shown in Table 1. Thin slices were cut from the consolidated specimens using a low speed diamond saw. A diamond drill was used to cut 3 mm disks which were then dimpled, ion-milled, and thin foils prepared by electropolishing in an electrolyte consisting of 5% H2SO4+95% methanol cooled to -25°C and at 175 mA and 25V. Transmission electron microscopy was conducted using either a Philips EM420T operating at 120 kV or a JEOL 2010 operating at 200 kV; typical microstructures are shown in Fig. 4. Grain sizes were determined using a linear intercept method (Table 1).

2.2. Ti-47.5Al-3Cr(at.%) alloy

The as-received gas-atomized prealloyed powder (~35