Microstructures and Properties for a Superalloy Powder Mixture Processed by Electron Beam Melting

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Received: May 31, 2012	Accepted: June 18, 2012	Online Published: June 28, 2012
doi:10.5539/jmsr.v1n3p124	URL: http://	/dx.doi.org/10.5539/jmsr.v1n3p124

Abstract

The microstructure and residual hardness for solid components of 2-phase TiAl (Ti-48Al-2Nb-2Cr in a_{0}) and Inconel 625 (Ni-22Cr-6Mo-2Nb in a_{0}) fabricated by electron beam melting (EBM) were compared with a 10:1 blend of TiAl: alloy 625 pre-alloyed powders producing a complex alloy having the composition 44Ti-39Al-7Ni-4Nb-4Cr-2Mo(in a_{0}). The blended alloy hardness (HV) reached 7.5 GPa in contrast to 1.4 GPa for the Alloy 625 and 4.0 for the 2-phase TiAl alloy.Reticulated mesh samples and stochastic foam samples prepared from the blended alloy by EBM exhibited a relative stiffness versus relative density plotted on a log-log basis consistent with other reference alloys fitted to a straight line with a slope n = 2 for ideal open cellular materials.

Keywords: electron beam melting, mixing TiAl & Ni-base superalloy, open-cellular structures, dynamic stiffness

1. Introduction

For many decades, Ni-base and Co-base superalloys along with Ni-Co-base superalloys and lighter weight/lowerdensity superalloys such as γ -TiAl-based alloys have served a wide range of high-temperature applications in aerospace and automobile industries. These include turbocharger innovations, engine exhaust valves, and turbine blades (including directionally grown single-crystal blades for jet engines) among others (Loria, 2005; Reed et al., 2008; Ott, 2011).

Ni-base superalloys such as Inconel 718 and 625 are also candidates for replacement of high-temperature ferritic/martensitic steel components in supercritical coal-fired power plants with the prospect of boosting operating efficiencies from around 36% to more than 47%, with reduced CO₂ emission for the same amount of energy production. This would require steam conditions of up to 760°C and 35 MPa (Viswanathan et al., 2005; Jablonski et al., 2012). Major concerns for superalloy use in these types of applications are characterized by demanding high-temperature, high-stress, corrosive (or oxidizing) environments (which can include a balance of damage tolerance), fracture toughness, fatigue strength, and creep resistance, especially in applications involving long turbine blades. Some aerospace applications often require small, complex-shaped components fabricated by near-net-shape metal injection molding (MIM) of metal-binder blends (Schmees et al., 1997). This wide range of property demands is accommodated by versatile microstructures which include varied grain sizes, precipitate types and sizes (γ' , γ'' , δ , etc.) and phase fractions (α_2/γ). Titanium aluminides have been shown to be inferior to both Ni-base and Co-base superalloys even if their density variations are considered in the context of a strength-to-weight basis: specific yield strength/density (σ_y/ρ); specific stiffness (E/ ρ); where E is the stiffness or elastic modulus and ρ is the density. For example, E for Ni-base superalloys is ~210 GPa and $\rho = 8.44$ g/cm³

(www.specialmetals.com) while for γ -TiAl, E \cong 165 GPa and $\rho = 3.8$ g/cm³ (Shafrik, 1977; Porter et al., 2003; Froes et al., 1992). Correspondingly, γ -TiAl-based alloys melt between ~1250°C and 1460°C while Ni-base superalloys melt between ~1330°C and 1425°C (Clemens & Kestler, 2000).

Powder-metallurgy-based methods, including MIM, are versatile routes for producing microstructure and property-engineered products through both powder blending and mixing, including the mixing of single element and pre-alloyed powders and the blending of micrometer-sized and nano-sized powders having these characteristics (Angel & Subramonian, 2009; Upadhyaya & Upadhyaya, 2011; Langlois et al., 2010). More recently, layer-by-layer fabrication of complex products from precursor powders by additive manufacturing using electron and laser beam melting processes have also extended the prospects for novel, powder-based, advanced manufacturing technologies, including opportunities for microstructure-property engineering by blending and mixing of elemental and pre-alloyed powders (Murr et al., 2012).

In this paper we explore the effect of selective mixing/blending a pre-alloyed TiAl-based powder with a pre-alloyed Ni-base (Alloy 625) powder on the development of solid and complex (open-cellular) components by electron beam melting (EBM). Of particular interest in this study was the comparison of microstructures and properties for 2-phase TiAl and alloy 625 (Inconel 625) components processed by EBM from pre-alloyed powders, with solid and open-cellular components produced by EBM from a 10:1 mixture of TiAl: alloy 625 powders.

We also fabricated open-cellular (mesh and foam) components and measured the dynamic Young's modulus or stiffness for varying densities. The relative stiffness versus relative density for these open-cellular components was also compared with other metals and alloys.

2. Experimental Methods

An Arcam A2 electron beam melting (EBM) system described in detail elsewhere (Murr et al., 2010, 2012) was used in this study to fabricate solid components from 2-phase TiAl powder and a Ni-base superalloy powder (Alloy 625). A 10:1TiAl: Alloy 625 powder mixture was also processed in the EBM system to produce solid (fully dense) components along with open-cellular components, including mesh and foam products with varying densities using CAD software models and lattice elements described elsewhere (Murr et al., 2010). These powders were mixed in a ratio of 10:1 TiAl: Alloy 625 to produce blended TiAl components by EBM. The melting point for the 2-phase TiAl powder was \sim 1460°C while the melting point for the Alloy 625 powder was \sim 1336°C.

Solid, fully dense specimens (cylinders or blocks measuring 1.5 cm diameter or several centimeters on a side) were fabricated from the 2-phase TiAl powder and the Alloy 625 powder. The TiAl components, having a density of ~3.85 g/cm³, were examined by optical metallography (OM), scanning electron microscopy (SEM) (employing an energy-dispersive X-ray spectrometer (EDS)), X-ray diffractometry (XRD) and transmission electron microscopy (TEM). Specimens for OM were prepared by polishing and etching in a solution consisting of 5 mL nitric acid, 10 mL hydrofluoric acid, and 300 mL water. Etching time was very short; only about 1s and specimens were immediately washed in ethanol to remove residual etchant. Polished and etched specimens were observed in a Reichert MEF4 A/M metallograph. Following OM analysis, the polished and etched specimens were examined in a Bruker AXS-D8 Discover XRD system using a Cu-target.

SEM analysis employed a Hitachi S-4800 field emission SEM fitted with an EDAX EDS system, and operated at either 20 kV or 30 kV accelerating potential in both the secondary electron (SE) or backscatter electron (BE) imaging modes. TEM analysis was carried out on ground, polished, punched, and electro-etched, 3 mm discs. Electroetching in a Tenupol-5 dual jet system utilized a solution consisting of 950 mL methanol and 50 mL perchloric acid at \sim 30°C. These electron transparent specimens were observed in a Hitachi H-9500 high-resolution TEM operating at 300 kV accelerating potential, fitted with a digital CCD camera and a goniometer-tilt stage (Hernandez et al., 2012).

For OM of Alloy 625 specimens, they were electroetched at 5V in a solution consisting of 20 mL phosphoric acid and 30 mL water. TEM specimens in the form of 3 mm punched discs were electropolished at ~-20°C in a solution consisting of 200 mL perchloric acid and 800 mL methanol, at 13 V (Murr et al., 2011). Blended TiAl components fabricated by EBM were examined using the protocols described above for the 2-phase TiAl components. This included series of mesh components having varying densities fabricated using the dode-thin lattice element (Murr et al., 2010) and stochastic foam components having different densities as well.

The dynamic stiffness (or Young's modulus, E) for the open-cellular, blended TiAl components was measured using a resonant frequency (fr) analyzer (IMCE-HTVP-1750-C) where $E \propto fr^2$. Rectangular specimens

measuring 2.5 cm x 2.5 cm x 5 cm were designed to satisfy the general requirements for metal foams discussed by Ashby et al. (2000).

Finally, residual, microindentation (Vickers) hardness (HV) was measured for all of the solid (and pre-alloyed powders) and open-cellular components using a Struers-Duramin A-300 digital instrumentation system; utilizing a 100 g f (1 N) load with a 10 s dwell time. A minimum of 10 indentations/sample were made. Macroindentation hardness measurements were also made on the solid-bulk components using a Rockwell tester with a 1.5 kN load, and a C-scale indenter (HRC). A minimum of 10 indentations were averaged for each specimen tested.

3. Resultsand Discussion

The starting powders included a 2-phase Ti-48Al-2Cr (atomic percent) pre-alloyed powder illustrated in Figure 1(a), having an average powder diameter of 52 μ m, and a 65Ni-26Cr-6Mo-3Nb (atomic percent) pre-alloyed powder illustrated in Figure 1(b); having an average powder diameter of 22 μ m. Table 1 shows comparative energy-dispersive X-ray spectrometer (EDS) analyses for the pre-alloyed powders in both weight percent and atomic percent along with the corresponding analyses for EBM-fabricated solid products. The 2-phase TiAl powder shown in Figure 1(a) had an equiaxed grain structure while the Alloy 625 powder shown in Figure 1(b) had a microdendritic structure. Figure 2 compares the X-ray diffraction (XRD) spectra for the two powders. Figure 2(a) shows a 2-phase α_2/γ mixture: γ -TiAl (fcc; a = 2.84 Å) and α_2 -Ti₃Al (hcp; a = 5.77 Å, c = 4.62 Å). Figure 2(b) shows the NiCr (fcc; a = 3.59 Å) matrix structure with a strong (111) texture for the Alloy 625 powder.



Figure 1. SEM views of pre-alloyed powder microstructure. (a) Gamma TiAl. (b) Inconel 625



Figure 2. XRD spectra for pre-alloyed powders. (a) Gamma TiAl. (b) Inconel 625

Inconel 625 Powder – EDS Data*			
Element	Wt. %	At. %	
Al	—	—	
Nb	3.0	2.0	
Ti		—	
Cr	18.8	24.3	
Ni	59.1	68.3	
Mo	7.6	5.4	
Total	88.5	100	
Element	Wt. %	At. %	
Element	Wt. %	At. %	
Al			
Nb	4.7	3.2	
Ti	—		
Cr	19.2	23.9	
Ni	61.1	67.1	
Mo	8.8	5.8	
Total	88	100	

Table 1. Chemical Composition for Pre-alloyed Powders and EBM Fabricated Solid Components

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TiAl Powder – EDS Data* Element Wt. % Al 33.80 Nb 4.92 Ti 58.74 Cr 2.54 Total 100	At. % 48.53 2.05 47.53			
Element Wt. % Al 33.80 Nb 4.92 Ti 58.74 Cr 2.54 Total 100	At. % 48.53 2.05 47.53			
Al 33.80 Nb 4.92 Ti 58.74 Cr 2.54 Total 100	48.53 2.05 47.53			
Nb 4.92 Ti 58.74 Cr 2.54 Total 100	2.05 47.53			
Ti 58.74 Cr 2.54 Total 100	47.53			
Cr 2.54 Total 100	1.90			
Total 100	1.07			
	100			
TiAl Solid Component – EDS Data*				
Element Wt. %	At. %			
Al 31.52	45.99			
Nb 5.36	2.28			
Ti 60.46	49.22			
Cr 2.66	2.02			
Total 100				

*20 kV accelerating potential

3.1 Comparative Microstructures for Solid Alloy 625, 2-Phase TiAl, and Blended TiAl

Figure 3 shows a 3D-OM composition for an alloy 625 solid cylindrical component fabricated by EBM. The 3D image shows 2 µm-spaced, columnar arrays of γ'' Ni₃Nb lenticular-like precipitates (bct: a = 3.62 Å, c = 7.41 Å) coincident with the NiCr (fcc: a = 3.59Å) matrix {111} planes. The 2 µm cellular-like arrays observed in the horizontal reference section also show low-angle grain boundaries (GB) characterizing columnar, oriented (and textured) grains. While these microstructural issues have been described in more detail in previous work (Murr et al., 2011a; Amato et al., 2012), Figure 4 shows a TEM bright-field image for the γ'' coincident precipitates approximating a vertical reference plane section shown circled at the arrow to the left in the 3D image of Figure 3. Precipitates along <112> directions in the (110) surface orientation shown in Figure 4 (at 2 and 3) are at 90° to the (110) specimen surface plane, and therefore represent the precipitate thickness which is observed to approximate 50 nm. Precipitates in the [$\overline{110}$] direction show by (1) in Figure 4 are coincident with (111) planes inclined 35° to the (110) spectra corresponding to the horizontal and vertical reference planes, respectively, corresponding to the 3D image composition in Figure 3. The prominent (220) or (110) texture illustrated in the vertical reference plane in Figure 5(b) corresponds to the (110) image view shown in Figure 4.

Figures 6 and 7 show corresponding 3D OM image compositions for the EBM fabricated solid blocks and cylinders of 2-phase TiAl and the blended TiAl powders, respectively. Figure 6 illustrates the dual-phase (duplex) α_2/γ , equiaxed grain structure composed of colony-lamellar substructures discussed in detail by (Froes et al., 1992; Appel et al., 2000; Hernandez et al., 2012).

Figure 7 shows for comparison the multi-phase, blended TiAl microstructure. These contrasting microstructures evident on comparing Figures 6 and 7 are illustrated in more detail on comparing corresponding TEM bright-field images for each as shown in Figure 8. Figure 8(a) shows the thin lamellar α_2 (hcp Ti₃Al) phase coincident with the γ -TiAl {111} planes while Figure 8(b) shows a complete absence of this lamellar microstructure within a multiphaseregion represented by the enclosure shown in the horizontal reference plane for the 3D image composition in Figure 7 for the blended TiAl.

The comparative XRD spectra representing the horizontal and vertical reference planes of the 3D OM image compositions in Figures 6 and 7 are shown in Figures 9 and 10. The XRD spectra for the duplex TiAl components shown in Figure 9 illustrate a generally $(101)\gamma$ texture for the equiaxed grain structure containing lamellar α_2 as shown in Figure 8(a). Correspondingly, the XRD spectra for the blended TiAl components shown in Figure 10 illustrate the complex, multiphase microstructure with peaks representing γ -TiAl, α_2 -Ti₃Al, NbCr₂ (laves phase), MoNb (bcc) phase, and Ni₃Al eutectic. The NbCr₂ laves phase was observed for EBM-fabricated and hipped alloy 625 (Murr et al., 2011) and has been observed in welded Inconel 718 by Radakrishna et al., (1995). In addition, MoNb precipitates were prominently observed in selective laser melted (SLM) and hipped

alloy 625 (Amato et al., 2012).

Table 2 shows the quantitative EDS elemental analysis corresponding to a blended TiAl section shown typically in Figure 7 along with comparative analyses for EBM-fabricated mesh and foam components to be described in detail later. In contrast to Table 1 corresponding to an accelerating voltage of 20 kV in the SEM, Table 2 shows elemental quantitation for 30 kV which is well above the excitation potential (~16-18 kV) for Mo and Nb. In addition, it should be noted that Mo and Nb L-line radiation peaks closely overlap in the EDS spectrum, while K α -spectra are more distinguishable at 30 kV.

Table 2.	Chemical	Composition	for Blended	TiAl Compo	onents Fabricat	ed by EBM
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Blended TiAl Solid Cylinder Component – EDS Data – 30kV				
Element	Wt. %	At. %		
Al	23.70	38.49		
Nb	8.34	3.94		
Ti	48.57	44.43		
Cr	4.50	3.79		
Ni	8.74	6.53		
Mo	3.84	2.82		
Total	97.69	100		

Blended TiAl Mesh Component – EDS Data – 30kV				
Element	Wt. %	At. %		
Al	23.42	37.94		
Nb	9.84	4.64		
Ti	53.78	49.08		
Cr	3.24	2.72		
Ni	4.12	3.29		
Мо	5.60	2.56		
Total	100.01	100.23		

Blended TiAl Foam Component – EDS Data – 30kV				
Element	Wt. %	At. %		
Al	22.48	37.03		
Nb	10.06	4.82		
Ti	51.83	48.10		
Cr	3.37	2.88		
Ni	5.08	3.85		
Mo	7.18	3.33		
Total	100	100.01		

Detailed X-ray mapping and quantitative elemental analysis was conducted for secondary electron (SE) and backscatter electron (BE) images for the blended TiAl components represented typically in Figure 7. Figure 11 illustrates an example of this analysis. Figure 11(a) shows a BE image for a horizontal reference plane section represented conceptually by the enclosure (box) in Figure 7. A larger phase region, representing the equiaxed "grains" in Figure 7, is shown at A in Figure 11(a). This region is bounded by another phase regime indicated by B, while within the A phase there are sub-phase regions marked C and D. D shown in the circled region in Figure 11(a) shows dark-contrast nanophases or precipitates. There are essentially 4 shades shown by A, B, C, and D in

Figure 11(a) representing essentially 4 different atomic number (Z) contrast regimes. Figure 11(b) to (d) illustrate elemental maps for Ti, Ni, and Mo, respectively corresponding to Figure 11(a); especially regions designated A and B. Region A is observed to be Ti-rich while region B is Ni-rich. Slightly more Mo is observed in region A, and the corresponding Nb map was observed to be identical to that for Mo in Figure 11(d). Al and Cr were observed to be distributed homogeneously, with the Cr concentration only roughly 20% of the Al concentration. While there is little Ni in phase region A in Figure 11(a), there is some Ti in region B. More detailed analysis of phases indicated by C in Figure 11(a) showed Ti₃Al plus a few atomic percent Nb and Mo while the darkest regions shown designated D in Figure 11(a) contained mostly Ti and Al; TiAl \cong 1:1 (in atomic percent). These regions contained about 3 atomic percent each of Nb, Mo, and Cr. Region A in general contained a Ti:Al ratio of 2:1 (atomic percent) and an Nb:Cr ratio of 1:2 (atomic percent). Region B in Figure 11(a) was dominated by a nominal 35Ti-45Al-14Ni composition.



Figure 3. 3D OM image composite section for an EBM fabricated Alloy 625 component. The build direction is shown by the lower right arrow. Grain boundaries are denoted GB



Figure 4. TEM vertical plane section view (parallel to the build direction in Figure 3; characteristic of the circled zone (arrow)). The grain surface orientation is (110). The trace directions shown correspond to $[1\overline{1}0]$ (1); $[1\overline{1}2]$ (2); $[\overline{1}12]$ (3)



Figure 5. XRD spectra corresponding to the horizontal (a) and vertical reference plane (b) for an Inconel 625 EBM-fabricated cylindrical component (Figure 3)



Figure 6. 3D Om image composite section for an EBM fabricated 2-phase TiAl component. The build direction is shown by the arrow (lower right)



Figure 7. 3D OM image composite section for an EBM fabricated blended TiAl component. The build direction is shown by the arrow (lower right)



Figure 8. TEM horizontal plane section views (perpendicular to the build direction). (a) 2-phase TiAl. (b) Blended TiAl



Figure 9. XRD spectra corresponding to the horizontal reference plane (a) and vertical reference plane (b) for a 2-phase TiAl EBM fabricated component



Figure 10. XRD spectra corresponding to the horizontal reference plane (a) and vertical reference plane (b) for a blended TiAl EBM fabricated component



Figure 11. SEM analysis sequence representing an area corresponding to the horizontal surface region shown in the box in Figure 7. (a) BE image showing complex phase structure and atomic number (Z) contrast. Phase regions are denoted A, B, C, D. (b) Ti X-ray map. (c) Ni X-ray map. (d) Mo X-ray map. (20 kV accelerating potential)

3.2 Open Cellular Mesh and Foam Components

Utilizing a stochastic foam element and a dode-thin reticulated mesh element, foam and mesh components measuring 2.3 cm×2.3 cm×3.5 cm height were fabricated with the following densities: foam: $\rho = 0.74$, 0.88, 1.00 g/cm³; mesh: $\rho = 1.02$, 1.11, 1.32 g/cm³. Figure 12 illustrates these EBM fabricated components. Figure 12(a) and (b) show the three mesh components viewed at 45° (face and diagonal or edge views: (a) and (b), respectively. Figure 12(c) shows the three corresponding foam components. Figure 13 shows mounted and polished sections for the 1.11 g/cm³ mesh (Figure 13(a)) and the 0.74 g/cm³ foam. The corresponding cylindrical mesh strut dimensions in contrast to the triangular foam ligament cross-sections can be observed on comparing Figure 13(a) and (b). In contrast to the regular strut arrays for the mesh components, the foam ligaments form along the edges of randomly packed polyhedral cells with 9 to 17 faces (Jang et al., 2008; Gibson & Ashby, 1997).

Figure 14 shows a horizontal reference plane section through a mesh component indicating zones of unmelted 2-phase TiAl powder particles. The enlarged view of a powder particle in Figure 14(b) (arrow) illustrates classical liquid-phase particle sintering showing a melt phase surrounding the 2-phase TiAl particle. These unmeltedTiAl particle zones were also observed in the ligaments for the foam components, and occur as a consequence of the very rapid cooling of the mesh and foam struts and ligaments in contrast to the solid components. This rapid cooling differentiates the higher melting point gamma-TiAl powder particle (~1460° C) from the lower melting point Inconel 625 powder particles (~1336° C) (Froes et al., 1992) which allows the Inconel 625 powder blend to melt preferentially in some areas. This sinter/melt phenomena in the open-cellular component fabrication also alters the complex phase mixtures and morphologies in contrast to the solid components. These features are apparent on comparing the 3D OM composites for the mesh and foam components shown in Figure 15 and 16, respectively, with the microstructure composite for the blended solid components represented by Figure 7. Figure 17 also compares the XRD spectra corresponding to the horizontal reference plane (perpendicular to the build direction) for the mesh (Figure 17(a)) and foam (Figure 17(b)) components. In contrast to the corresponding XRD spectra for the solid blended TiAl components in the horizontal reference plane in Figure 10(a), there are subtle variations in peak intensities. It can be observed on careful comparison of Figure 7 with Figures 15 and 16, that the phase morphologies and sizes for the open-cellular components are similar in both the horizontal and vertical reference planes which are also similar to the vertical reference plane microstructure shown in Figure 7. The horizontal reference plane microstructures/phase structures in Figure 7 are somewhat different but as illustrated in Figure 11(a), the phase sizes range from ~ 100 nm to ~ 5 µm within stoichiometrically different zone or grain structures measuring ~ 10 μm. A similar range of size features are also observed in Figures 15 and 16 although the phase morphologies are different. The BE image in Figure 18 illustrates this feature for the horizontal reference plane for a mesh strut, corresponding to Figure 15. The phase compositions are referenced to the solid blend shown as A, B, C, and D in Figure 11(a).





Figure 12. EBM-fabricated open-cellular structures. (a) Mesh components observed in the face plane. Arrow shows the build direction. (b) Mesh components observed along an edge at 45° to the face view in (a). Densities shown in units of g/cm³. (c) Foam components observed in the face plane. Densities shown in units of g/cm³



Figure 13. Blended TiAl mesh (a) and foam (b) cross-sections in the top face section perpendicular to the build direction. (a) corresponds to a density of 1.11 g/cm³; (b) corresponds to a density of 0.74 g/cm³



Figure 14. Polished and etched section for a mesh strut shown in Figure 13(a). Unmelted, liquid-phase sintered TiAl powder particles are observed in (a). (b) shows a magnified view of (a) (arrow)



Figure 15. 3D OM composite for a mesh strut cross-section. The build direction is shown by the arrow



Figure 16. 3D OM composite for a foam ligament cross-section. The build direction is shown by the arrow



Figure 17. XRD spectra for blended TiAl mesh strut and foam ligament section. (a) Horizontal reference plane for a mesh strut. (b) Horizontal reference plane for a foam ligament



Figure 18. Backscatter electron (BE) image showing phase morphologies and stoichiometries referenced to Figure 11(a): A, B, C, and D

3.3 Hardness Measurements and Comparisons

Figure 19 summarizes the hardness averages for solid EBM components of Inconel 625 and 2-phase TiAl in contrast with the precursor powders and blended TiAl solid and open-cellular (mesh and foam) components. Note that HRC measurements were not possible for the powders and, mesh and foam components, while HV measurements were made for all of the samples. It is interesting to note the significant hardness increase for the blended TiAl solid components in contrast to both of the mixed powders (Inconel 625 and TiAl). The increase in the solid blend over the 2-phase TiAl is observed to be ~40% in Figure 19. Correspondingly, the blended TiAl mesh and foam hardness increased ~30% relative to the TiAl solid components, although the Vickers microindentation hardness (HV) for the precursor (pre-alloyed) 2-phase TiAl powder remained the same for both the EBM-fabricated mesh and foam components from blended TiAl powder.





3.4 Measurement of Dynamic Stiffness for BlendedTiAl Mesh and Foam Components: Implications for Ideal Foam Model

Gibson and Ashby (1982) considered a simple lattice element structure similar to the mesh element utilized in this study, consisting of short, connected struts described by Timoshenko-type beams (Timoshenko & Gere, 1972) to derive a general open-cellular element relationship in the form:

$$E/E_{o} = C_{1} \left(\rho/\rho_{o}\right)^{2} \tag{1}$$

Where E_o is the fully dense (solid) modulus (or dynamic stiffness) having a density ρ_o , and C is a constant. This ideal model has been demonstrated to fit a wide range of foam materials including polymers, aluminum and aluminum alloys, and other alloys (Gibson & Ashby, 1982; Murr et al., 2011b).

Table 3 lists the measured stiffnesses (E) and corresponding densities (ρ) for the blended TiAl foam and mesh components shown in Figure 12. Attempts to measure the fully dense ($\rho_o = 4.13 \text{ g/cm}^3$) stiffness were unsuccessful because the solid, blended TiAl components were so brittle they shattered when impacted for resonant frequency production. This behavior is somewhat consistent with the high hardness as shown in Figure 19 and the presence of brittle phases such as NbCr₂ laves (Radakrishna et al., 1995) and the eutectic Ti₃Al and Ni₃Al phases. Consequently, in order to approximate the solid (dynamic) Young's modulus, we plotted values of

E in Table 3 against corresponding densities (ρ), and extrapolated the fitted line in the log-log plot to $\rho = \rho_0 = 4.13 \text{ g/cm}^3$ as shown in Figure 20. The corresponding stiffness (E_0) was found to be 135 GPa at $\rho = \rho_0$ (Figure 20). This value of stiffness, $E = E_0 = 135$ GPa was employed to calculate relative stiffness values (E/E_0) as shown in Table 3, and these values were plotted against relative density values (ρ/ρ_0) as shown in the log-log plot in Figure 21; in comparison with data for Ti-6Al-4V where $E_0 = 110$ GPa, and a Co-base superalloy where $E_0 = 210$ GPa (Murr et al., 2010, 2011b). The data in Figure 21 is very closely fitted to a straight line with n = 2. This is especially notable because the blended TiAl alloy is very complex, and taken together with other relative stiffness versus relative density log-log plotted data (Murr et al., 2010, 2011b, 2012) strengthens the case for metal alloy open-cellular structures generally following the ideal foam relationship shown in eqn. (1).

5	5			2 (/
Sample	Density	Stiffness	ρ/ρ_o*	E/E _o *	Porosity [†]
	ρ (g/cm ³)	E (GPa)			(%)
Foam	0.74	1.81	0.19	0.010	81
Foam	0.88	3.42	0.23	0.020	77
Foam	1.00	4.00	0.26	0.023	74
Mesh	1.02	3.43	0.26	0.020	74
Mesh	1.11	4.40	0.29	0.025	71
Mesh	1.32	7.31	0.34	0.040	66

Table 3. Dynamic Stiffness and Density Measurements for TiAl/Ni-Cr Alloy (Blended TiAl)

* Solid density, $\rho_0 = 4.13$ g/cm³; solid stiffness, $E_0 = 135$ GPa, E_0 was determined graphically from Figure 20; at $\rho = 4.13$ g/cm³ for log-log plot of E versus ρ .

[†] Porosity calculated from density (ρ); porosity = (1- ρ/ρ_0) 100%



Figure 20. Log-log plot of measured stiffness versus density for the blended TiAl mesh and foam samples



Figure 21. Log-log plot of relative stiffness versus relative density for blended TiAl mesh and foam components (indicated by Ti-Al alloy) in comparison with Ti-6Al-4V and Co-based alloy data from Murr et al. (2010, 2011b)

4. Summary and Conclusions

The mixing or blending of powders to produce novel alloy systems by additive manufacturing has been explored in this paper involving a 10:1 mixture of 2-phase TiAl: Inconel 625 alloy; having average powder particle sizes of 52 µm and 22 µm, respectively. The blended alloy produced a hardness increase of more than 30 percent over the hardest component in the mix, but there was no elongation corresponding to a very brittle solid product. Because a systematic study of powder mixing ratios was not performed in this study, it is not possible to speculate on the much higher hardness developed. Additional, more systematic studies may shed some light on design strategics for alloy development using powder mixtures in electron beam melting. Nonetheless, open-cellular mesh and foam components exhibited relative stiffness versus relative hardness values fitted to an ideal foam log-log line slope for n = 2. This finding supports the prospect that essentially any metal or alloy open-cellular structure will generally follow the ideal foam relationship: $E/E_o = (\rho/\rho_o)^2$. The implications of this work are that powder mixing or blending may provide a viable route to fabricate unique alloy systems, but considerably more systematic studies will be required to establish clear trends or routes for specific property development.

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