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Mechanical Properties of Cast Ti-6Al-2Sn-4Zr-2Mo Lattice Block Structures**

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Lattice block structures (LBS) – also called lattice-truss structures, truss-core sandwiches, and cellular lattices – have been fabricated from alloys of aluminum,[1–3] copper[2] and iron.[4] Three methods for fabrication of titanium LBS have been reported so far in the literature, to our knowledge. In a first method, struts consisting of a thick slurry of Ti-64 powders in an organic binder are layered into a 0/90 degree pattern forming the LBS which is sintered after binder removal.[5] In a second, related method,[6,7] selective electron beam melting is used to melt titanium and Ti-64 powders under high vacuum layer by layer, resulting in a structure with relative density of 30 %[6,7] characterized by struts, less than 1 mm in diameter, arranged in various architectures.[6,7] Finally, we recently showed that LBS panels with 1.6 and 3.2 mm diameter struts could be investment-cast with the alloy Ti-64, and we studied the mechanical properties of struts and panels at ambient temperature.[8] Such investment-cast titanium panels combine the advantages of high strength derived from the periodic LBS architecture, high mechanical performance inherent to titanium alloys, and low cost from casting. The present paper describes the mechanical properties, at ambient and elevated temperatures, of investment-cast Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) LBS panels. This alloy was chosen because it exhibits improved stiffness and strength at ambient temperature as compared to Ti-64, as well as much improved microstructural stability and mechanical strength up to 565 °C,[9] while remaining castable.

The Ti-6242 LBS panels were investment-cast in vacuum using the lost-wax approach, following a technique described previously,[2,8] After casting, panels were processed according to standard aerospace-grade titanium casting procedures (AMS 4985B). First, hot isostatic pressing (HIP) was performed at 900 °C for 2 hrs under a pressure of 103 MPa, a treatment commonly used to close casting porosity.[11] This was followed by chemical milling to remove the α-case, NADCAP-approved nondestructive inspection (visual, radiographic, penetrant), casting weld repair as necessary, and a mill-anneal heat-treatment carried out at 730 ± 15 °C for 2 hrs, terminated by furnace cooling, and then final inspections and light etching.

Figure 1 shows a ~ 100 × 100 × 25 mm^3 panel consisting of a core with 3.2 mm diameter struts in a pyramidal arrangement and two faces which consist of a square external frame (with approximate 3.8 × 6.4 mm^2 cross-section) filled by a

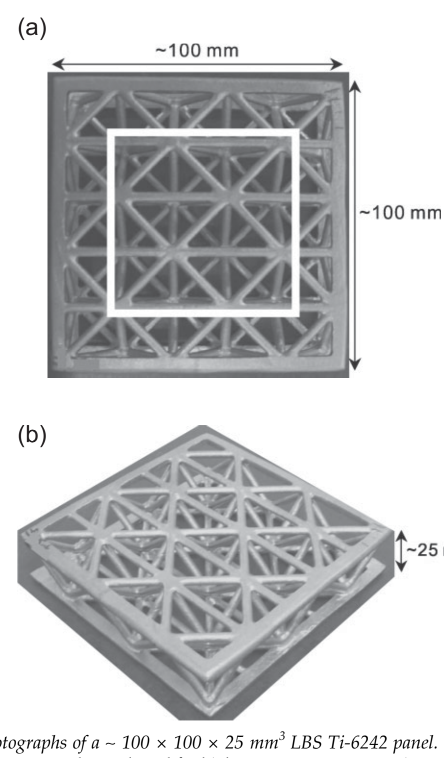

Fig. 1. Photographs of a ~ 100 × 100 × 25 mm³ LBS Ti-6242 panel. The white square highlights a 3 × 3 sub-panel used for high temperature compression tests. (a) Top view; (b) Perspective view.

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triangular planar array of 3.2 mm diameter struts. This is the same architecture as that reported previously for a Ti-64 panel.[8] Some of the struts are not exactly cylindrical, as they exhibit small depressions on their surface due to irregularities of the patterns as well as pore closure from the HIP process. The average density of the panels (calculated by dividing the panel mass with its volume, taken as the outside envelope defined by the upper and lower frames) is 0.73 g/cm^3, corresponding to 16 % of Ti-6242 bulk density (4.54 g/cm^3).[9]

The microstructure of one node sample and two strut cross-section samples (parallel and perpendicular to the strut axis) is displayed in Figure 2 and is characteristic of the Widmanstatten morphology typically found in cast Ti-6242;[10] prior-β grain-boundaries are also visible, outlining prior-β grain with ~ 0.5 mm size. The density of 18 struts, cut from the panels, was measured as 100.5 ± 1.5 %, indicating that closed porosity was absent.

Individual struts with 2.0–2.2 aspect ratio were cut from the panel core using a diamond saw. Their sides were left in the as-cast condition, and their ends were machined to insure good parallelism. Three struts were tested in compression at ambient temperature with a cross-head speed of 0.2 mm/min. The engineering stress is calculated by dividing the load by the original area of the strut, and the engineering strain by dividing the strut length change (determined from a laser extensometer) by its original length. The stress-strain curves are shown in Figure 3. The Young's modulus is 117 ± 24 GPa, within the 116–119 GPa range given by literature.[9] The yield strength is 1230 ± 73 MPa, slightly higher than the 1080–1170 MPa literature range.[9] Finally, the peak strength is 1850 ± 93 MPa. Struts were also subjected to ambient-temperature three-point bend testing at a cross-head speed of 0.3 mm/min, using a span of 15 mm. Figure 4 reports load-displacement curves for the tests. Fracture strength is 2070 ± 84 MPa. Compared with Ti-64 struts with the same diameter, Ti-6242 struts have higher compressive yield and peak strengths and lower bending fracture strength. Ti-6242 struts also have a lower bending ductility than Ti-64 struts since the maximum displacement is 0.6–0.9 mm for Ti-6242 struts and 1.4–1.8 mm for Ti-64 struts.

A 900 kN capacity testing machine was used to deform in uniaxial compression a full-size panel (with a mass of 184 g)

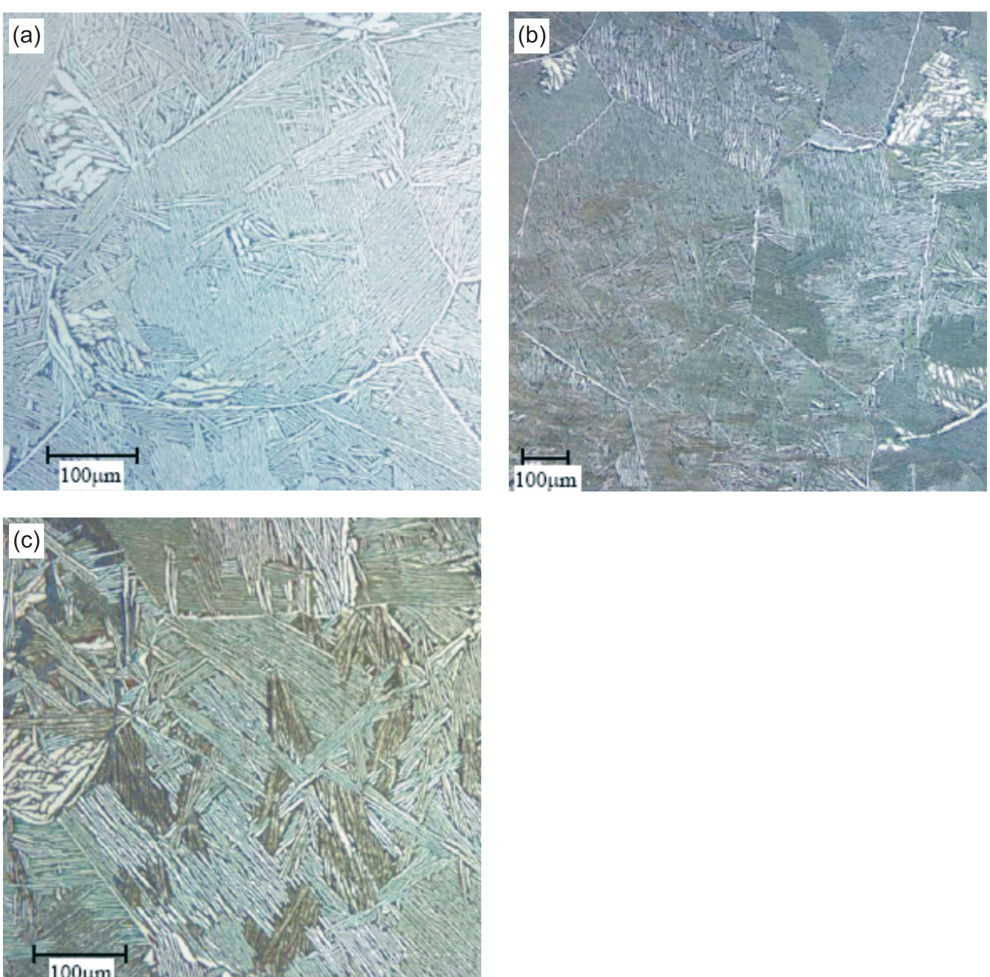

Fig. 2. Optical micrographs of (a) node at the intersection of struts; (b) strut cross-section parallel to strut axis; (c) strut cross-section perpendicular to strut axis.

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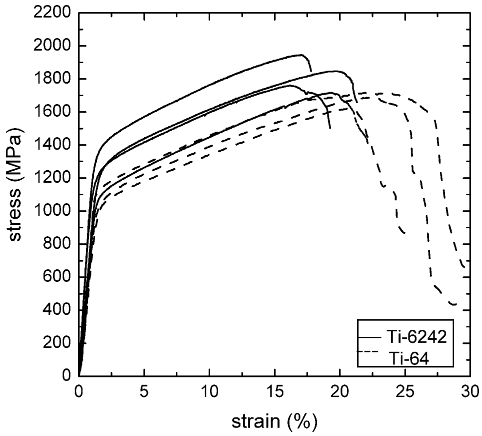

Fig. 3. Compressive stress-strain curves for three Ti-6242 struts and four Ti-64 struts [8] at ambient temperature.

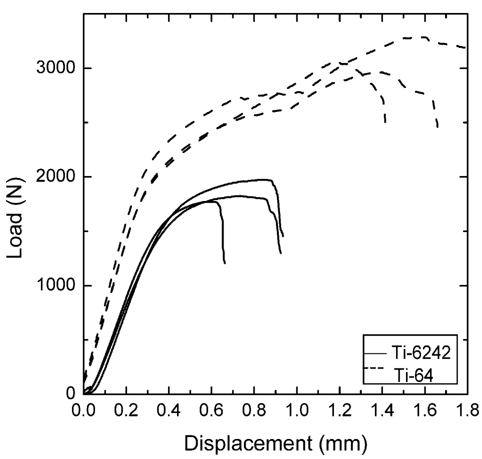

Fig. 4. Bending load-displacement curves for three Ti-6242 struts and three Ti-64 struts [8] at ambient temperature.

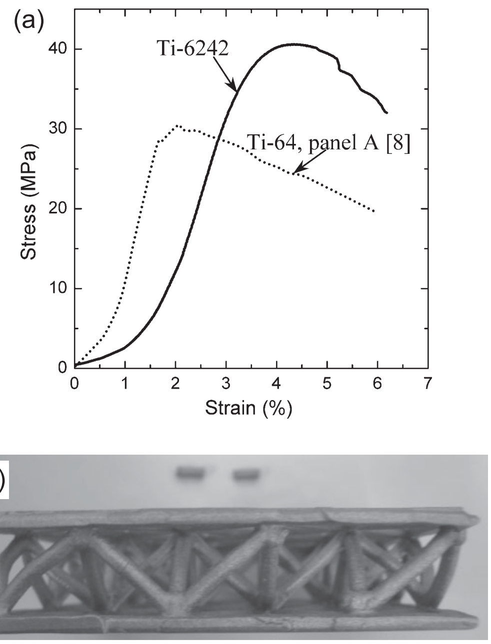

Fig. 5. (a) Compressive stress-strain curves for a Ti-6242 LBS panel and Ti-64 LBS panel, [8] both with same relative density of 16.0 %, tested at ambient temperature. (b) Photograph of deformed Ti-6242 panel under room temperature compression.

at ambient temperature at a crosshead displacement rate of 0.5 mm/min, using contact extensometry to measure strain. The panel deforms primarily by bending of the core struts, as shown in Figure 5 (b); one strut also ruptured during testing. Figure 5(a) presents the stress-strain curve of the panel. The maximum load carried by the panel is 385 kN, corresponding to an ultimate stress of 41 MPa. The elastic modulus is 2.0 GPa and the yield strength is 35 MPa. This value is about 2.8 % of the yield strength of the corresponding struts (1230 MPa). For an aluminum alloy LBS with an architecture similar to ours but a slightly lower relative density of 13 %, a panel yield strength of 3.4 MPa was found, corresponding to a 2.9 % fraction of the 118 MPa yield strength of the struts.[2] As reported in Ref.[8] a cast Ti-64 LBS panel with the same architecture and the same relative density of 16 % as the present Ti-6242 panel exhibited a yield strength of 29 MPa. This value is 20 % lower than the 35 MPa value measured for the present Ti-6242 panel, but it represents a slightly higher fraction (3 % vs. 2.8 %) of the strut strength (1030 MPa). The present Ti-6242 panel also shows a Young's modulus of 2.0 GPa (as measured in the steepest part of the stress-strain curve in Fig. 5). This is lower than the 2.9 GPa value found for a previous Ti-64 panel, despite the fact that Ti-6242 shows a higher stiffness (116–119 GPa) than Ti-64 (105-116 GPa).[9] This discrepancy may originate from the non-linear behavior of the panel in the elastic range, probably due to slight misalignment during testing resulting from lack of exact parallelism between the two faces of the sandwich.

High-temperature compression tests were performed at 482 °C and 315 °C on 3 × 3 square sub-size panel samples, as sketched in Figure 1(a). Strain was determined from crosshead displacement (held constant at 0.1 mm/min) after correction for system compliance measured independently. Prior to testing, the sample was equilibrated for about 30 min at temperature in air. The mass of the samples tested at 315 and 482 °C were 51 and 56 g, respectively. Figure 6(a) gives the stress-strain curve of the tests. The sharp drops for the 315 °C curve correspond to struts failure in the panel during the test. Figure 6(b) shows a photograph of the sample after testing at 482 °C, illustrating the extensive bending of the core struts. Yield strength at 315 and 482 °C are 20 and 17 MPa respectively, which are about 57 and 49 % of the ambient temperature value. As expected, the yield strength drops and the ductility improves with increasing testing temperature.

In summary, Ti-6242 lattice block structures were produced by investment casting with near-zero casting porosity after a standard HIP treatment. Individual struts exhibit the nominal compressive strength of cast Ti-6242 as well as good bending ductility. Compression tests of panels at ambient temperature indicate that the panel strength, which is controlled by strut bending, is about 2.8 % of the yield strength of the corresponding struts. This proportion is similar to that reported previously for Ti-64 and aluminum LBS panels with

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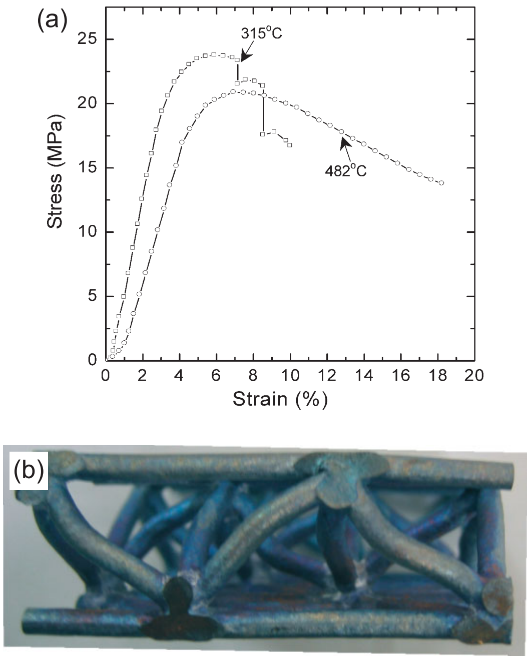

Fig. 6. (a) Compressive stress-strain curve for 3 × 3 sub-size panels at 315 and 482 °C. (b) 3 × 3 Ti-6242 sub-size panel sample after compression testing at 482 °C. The bluish color is due to oxidation.

the same architecture and similar relative density.[2,8] The panel yield strength at 315 and 482 °C are about 57 and 49 % of the ambient temperature value of 35 MPa, and the panel ductility increases with temperature.

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