ARMY RESEARCH LABORATORY

Mechanical Response of Titanium Aluminide ($TiAl_3$)

by Ajmer Dwivedi and Jermaine Bradley

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prepared by

Dynamic Science, Inc.
1003 Old Philadelphia Rd., Suite 210
Aberdeen, MD 21001

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1. Introduction

Laminated materials are commonly used to combine desired features of two or more materials; some examples include glass fiber reinforced aluminum (GLARE) and layered titanium–carbon fiber materials. In addition, there is interest in the use of laminated materials for light-weight vehicle armor. Laminates of titanium and aluminum alloys, manufactured by Solidica, Inc., have been evaluated at the U.S. Army Research Laboratory (ARL) for ballistic performance. These materials are made by a process known as Ultrasonic Consolidation (UC) in which acoustic waves are used to join foils of alternating layers of titanium and aluminum, creating a bulk material with reasonable interface strength. This bond strength can be increased by heat-treating in such a way that the material at the interface reacts to form the intermetallic material Titanium Aluminide ($TiAl_3$), creating in effect a three-material laminate.

Because intermetallics tend to be brittle, the addition of this third component is not without consequences. In an effort to understand the complete system, the ballistic evaluations mentioned above are being accompanied by numerical simulation, and the mechanical properties of each material must therefore be known. Although there is an abundance of data available for numerous titanium and aluminum alloys, this is not the case for $TiAl_3$. To satisfy this lack of data, a series of compression tests were performed on $TiAl_3$ at rates ranging from 0.00003 to 500/s using both a servo hydraulic load frame and the Split Hopkinson Pressure Bar (SHPB) method. These experiments are the subject of this report.

Although there is no compression data on $TiAl_3$ available in the literature, some relevant work has been done on similar metal–intermetallic laminate (MIL) composites. For example, the effect of internal stresses on the fracture toughness of Ti-Al_3Ti composites has been investigated and compared with computational results by Li et al. (2004). Similarly, Peng et al. (2005) studied the mechanical and fracture behavior of Ti-Al_3Ti that was produced by reactive sintering in a vacuum. The spall response of various ultrasonically consolidated Ti/Al laminates (also manufactured by Solidica and closely related to the current program) was studied in gas gun experiments and reported by Sano et al. (2009).

The remaining document is organized as follows. More details of the material studied here and its processing are given in section 2. The experimental techniques are described in section 3. The results are presented in section 4, along with a discussion of the results, which includes a fairly large specimen-to-specimen variation in observed behavior. Because of the brittle nature of $TiAl_3$, and its low-strain to failure, this material is difficult to test, especially at elevated strain-rates. This problem is further compounded due to the difficulty in manufacturing $TiAl_3$ in sizes large enough for mechanical testing. It is suspected that defects in the material due in part to manufacturing partially explain the variation of these results, especially in terms of the fracture behavior. More details are given in section 4.

2. Material

All specimens discussed in this report were provided in their as-tested condition by Solidica, Inc. The plate from which they were machined was manufactured using UC of foils of commercially pure titanium and Al 1100-O. The foil thicknesses are proprietary. The laminate is built up by rolling over each foil individually with a sonotrode that produces high frequency ultrasonic waves. The resulting friction causes the foil to become bonded to the layer beneath it. Following this process, the plate was pressed and heated (details proprietary). This results in the formation of fully consolidated $TiAl_3$. Scanning Electron Microscopy (SEM) scans of sectioned material indicate that the material is fully reacted.

Using a buoyancy method the density of the $TiAl_3$ was found to be 3282 kg/m^3. The longitudinal and shear wave speeds were found using an ultrasonic pulse echo technique; for an example, see Bartkowski and Spletzer (2001). The wave speeds and elastic constants calculated from these values are reported in table 1. There was a significant amount of variation in the measurements due to specimen quality. The first and second pictures in figure 1 show surface flaws and incomplete layer bonding, respectively. The presence of these defects in the specimens negatively affected wave propagation through the material and caused variation in the data. Values for the highest quality specimen (#2, not pictured) were used for calculations found later in this report.

Specimens for the compression tests did not contain the obvious defects seen in figure 1, however, some surface irregularities (non-smoothness) were easily detectable with the naked eye. Unfortunately defects of this nature can serve as nucleation sites for fracture and affect the results discussed below.

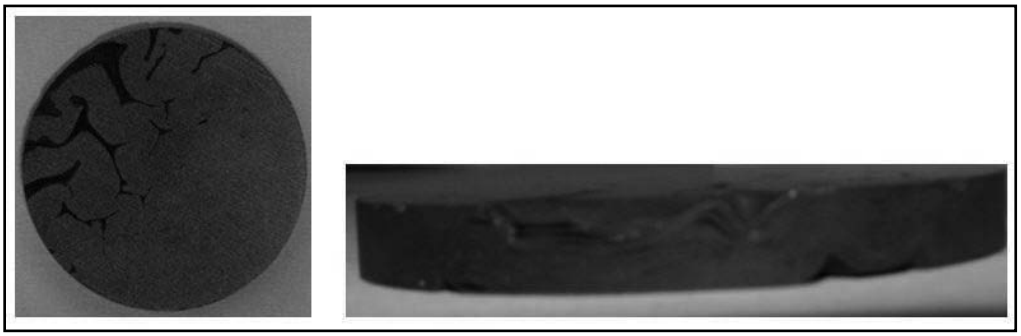

Figure 1. Photos of specimens used for ultrasound measurements.

Table 1. Wave speeds and elastic constants for $TiAl_3$.

Specimen	Longitudinal Wave Speed	ShearWave Speed	K	E	G	ν
#	*(km/s)*	*(km/s)*	*(GPa)*	*(GPa)*	*(GPa)*	
1	7.6	4.7	91.8	171.5	72.1	0.189
2	7.7	4.7	97.0	176.9	73.9	0.196
3	7.7	4.5	102.5	165.5	67.2	0.231

3. Experiments

3.1 Low Rates

Low-rate compression experiments were performed at strain rates between 0.00003/s and 0.002/s using an Instron model #1331 servo-hydraulic load frame and an Instron 48.9-kN load cell. The test matrix is shown in table 2, and lists a variety of techniques used to improve the data. By their nature, brittle materials like $TiAl_3$ deform only minimally before failure, and these small deformations can be difficult to measure with traditional cross-head measurements of displacement.[1] This proved to be the case with these experiments, specifically specimens #1 and 2. To overcome this, specimens 3–10 were instrumented with strain gages (Vishay Micro-measurements gages used: either EA-06-031DE-350 or EA-06-031EC-350) bonded to their surface to measure longitudinal strain directly. The only difficulty that arises here is that in some cases, one or more gage became unbounded from the specimen during loading and the strain measurement was lost prior to specimen failure.

Brittle materials can also be sensitive to non-centric loading due to non-parallel platens or even from their own loading surfaces. Three techniques were used to mitigate these issues. To eliminate any initial "settling" that was contributing to irregularities in the data some samples were loaded twice. In the table the notation "a" denotes a test where the specimen was loaded to a point below the yield stress and released. The "b" notation refers to the experiment in which the same specimen was compressed to failure. To deal with possible specimen irregularities, the loading faces of specimens 6–10 were finished (600 grit) with an Allied Techprep polisher, a machine designed for precise parallel polishing. Finally, specimens 7–10 were loaded with a spherically articulating platen in line with the load cell. This platen rotates slightly to minimize effects due to non-parallel load faces of either the specimen or the machine. A sketch of this test setup is shown in figure 2.

[1] Machine compliance corrections were used in all analyses, and all specimens were loaded between Tungsten Carbide platens and lubricated with MoS_2 grease.

Table 2. Test matrix for low rate experiments.

Test Number	Strain Gages	600 Grit Finish	Curved Platen
1	—	—	—
2	—	—	—
3	X	—	—
4	X	—	—
5	X	—	—
6a	X	X	—
6b	X	X	—
7a	X	X	X
7b	X	X	X
8a	X	X	X
8b	X	X	X
9	X	X	X

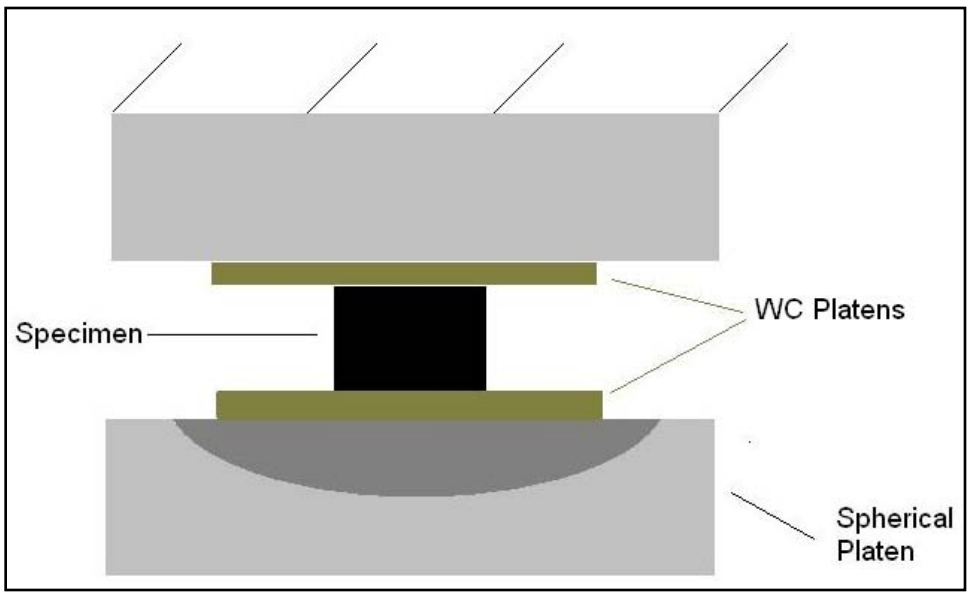

Figure 2. View of test setup with spherical platens.

3.2 High Rate

A Compressive SHPB (Follansbee, 1985) was used to achieve high rates, approximately 400/s. The bars were 9.525-mm diameter and made from Vascomax C350 Maraging steel. Because the specimens essentially behave elastically, pulse shaping was used to tailor the incident pulse to a ramp loading such that the specimens deformed at reasonably uniform strain-rates. All tests utilized the same shaper–a 0.8-mm thick piece of copper with a diameter of 9 mm. A total of five tests were conducted. The same difficulties encountered with the low-rate tests exist here, specifically, the small strain measurements. Strain gages were bonded to the specimens used in tests 3–5 to make more accurate strain measurements than those from the SHPB analysis.

Similar techniques for pulse shaping and making small strain measurements have been documented in recent literature (Blumenthal and Gray, 1990; Nemat-Nasser et al., 1991; Ravichandran and Chen, 1991, 1997).

4. Results and Discussion

4.1 Low Rate

As discussed above, most of the experiments were not well-suited to measure stress-strain curves and only the failure stress. All of the specimens failed catastrophically with little noticeable plastic deformation, see for example the recovered specimen in figure 3. This sort of behavior is typical of ceramic-like materials. Also, because of its low ductility, it is reasonable to assume $TiAl_3$ to be linear elastic to failure ($\sigma = E\varepsilon$). To evaluate the accuracy of this assumption the stress-strain curves shown below include the assumed linear elastic curve with slope equal to the measured elastic modulus from table 1.

Figure 3. Typical failed low rate specimen.

Figure 4 shows the stress-strain curve from Test #5. Specimen strain is measured with a strain gage mounted on the specimen. In light of the error associated with the small strain measurements the data is in good agreement with the assumed elastic modulus. It is noteworthy that at 230 MPa it appears as though the material begins to yield. It is unclear whether this portion of the graph represents actual material behavior or is the result of gage error. This specimen failed at a stress of 300 MPa, i.e., the strain gage survived the entire test.

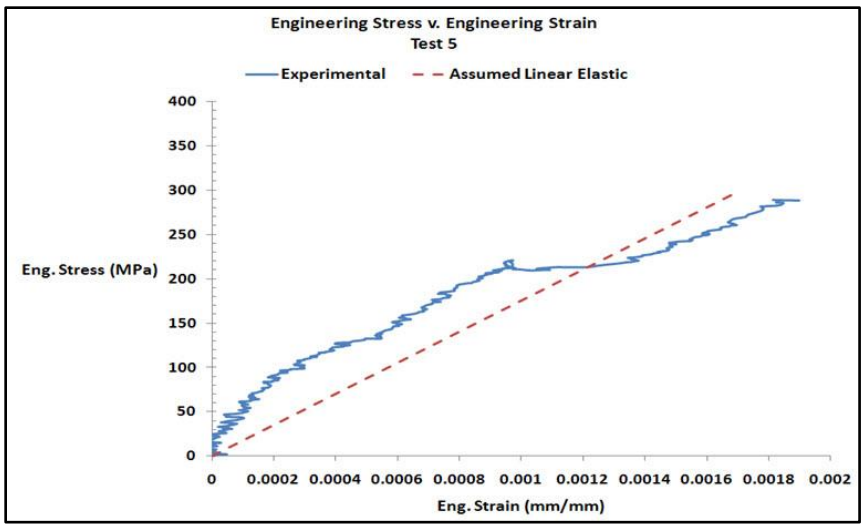

Figure 4. Stress–Stain curves calculated from strain gage data and theoretical linear elastic behavior based on ultrasound measurements.

The results from Test 6b are shown in figure 5. Two strain gages were bonded to this specimen, diametrically opposed and oriented to measure longitudinal strain. The figure only shows the material response up to gage failure. During Test 6a, the initial loading of this specimen, not pictured) the gages did not measure identical strains, indicating some non-centric loading that was reduced as a result of the preloading. The elastic modulus from the data in figure 5 is approximately 131 GPa, about one quarter less than the value measured from ultrasound. It is, however, strongly linear.

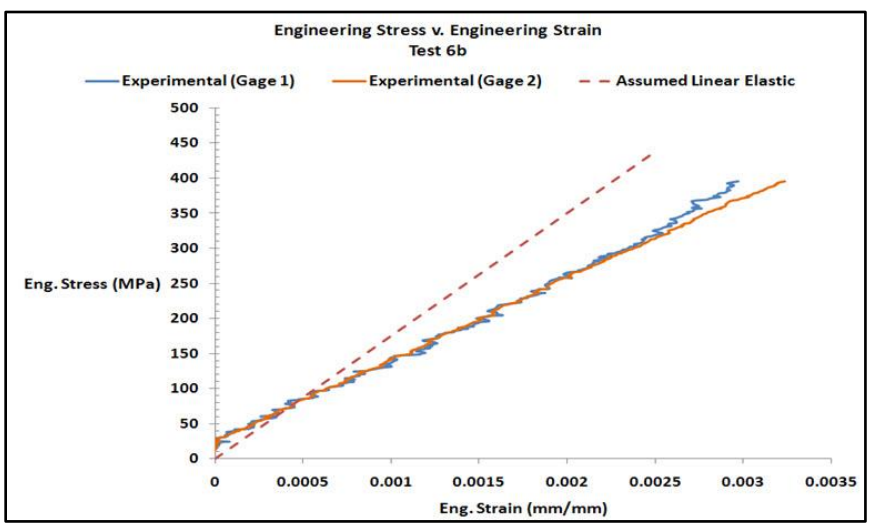

Figure 5. Stress–Strain curve for pre-loaded specimen compared to theoretical linear elastic curve.

Tests 7a and 7b repeated the previous experiment, but incorporated a spherical platen. The results are shown in figure 6. The data suggests that an initial stress of 50 MPa was attained before the specimen began to compress, but this is attributed to measurement error rather than

actual material behavior. The specimen response was linear in both tests and was reasonably close the linear elastic line. This setup was used to conduct several more experiments, and yielded somewhat inconsistent results due to specimen variation.

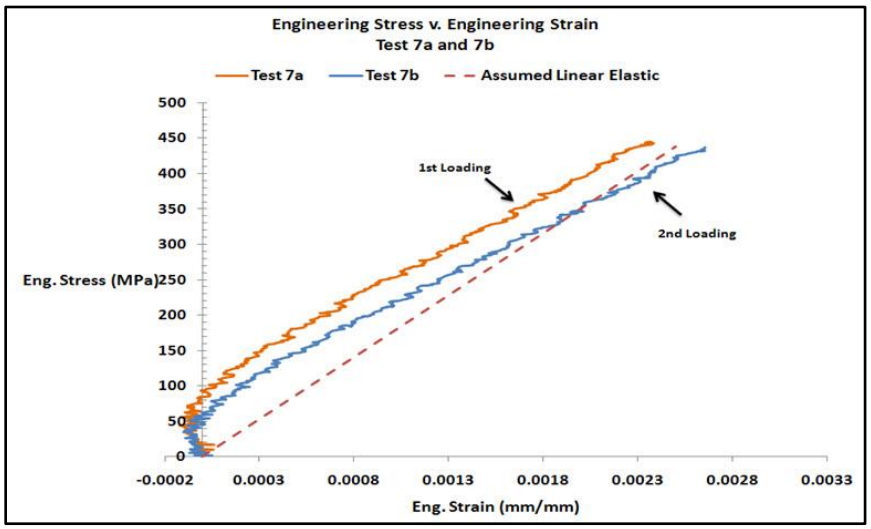

Figure 6. Stress–Strain curves for Tests 7a and 7b incorporating spherical platen.

The failure stresses for each of the low rate experiments are reported in figure 7, and the strain rates can be found in table 3. As expected, there was difficulty pinpointing a single failure stress for the material as illustrated by the scatter in the graph. Despite incorporating a spherically articulating platen and sanding specimens the variation persisted. Defects in the specimens arising from the manufacturing process are suspected to be the cause of the scatter.

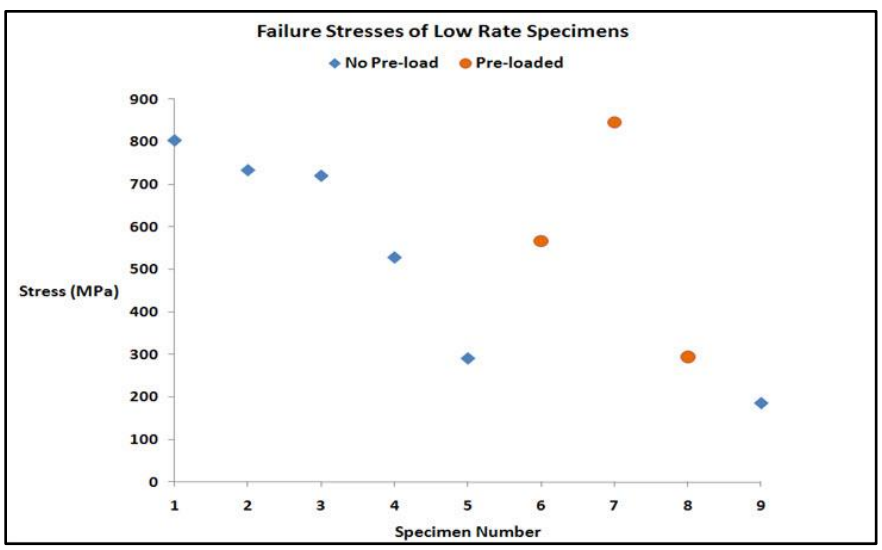

Figure 7. Failure stresses of low rate specimens.

Table 3. Strain rates for quasi static compression tests.

Test Number	Strain Rate
	(1/s)
1	0.00005
2	0.00005
3	0.002
4	0.0001
5	0.00008
6a	0.0002
6b	0.0002
7a	0.00009
7b	0.00009
8a	0.00005
8b	0.00009
9	0.00003

Note: The specimens used in Tests 1 and 2 did not have strain gages; their rates were estimated from similar tests.

4.2 High Rate

Figure 8 shows representative time dependent strain signals from one of the SHPB tests. The red and blue curves are the strain pulses that occur in the incident and transmission bars, respectively. The incident pulse is triangular due to the copper wave shaper that was placed on the impact end of the bar. Using the shaper allowed specimens to be tested at a constant strain rate and reduced wave dispersion in the bars. The green curve represents the data acquired from the strain gage on the specimen. The gage data shows that in this test the specimen was compressed at a roughly constant rate to approximately 6000 micro-strain, at which point it began to unload. The signal does not return to zero because some plastic strain was experienced.

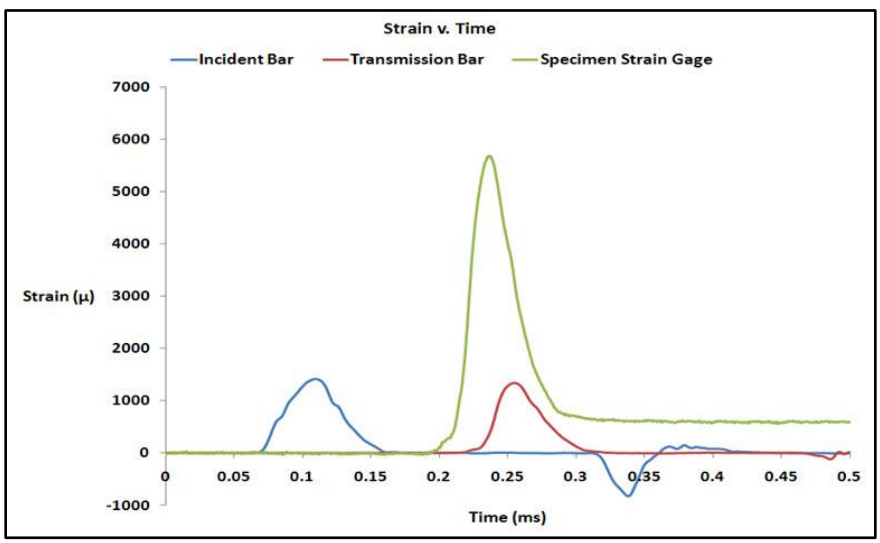

Figure 8. Strain signals from SHPB test.

A stress strain curve was calculated from the signals in figure 8 and is shown in figure 9. The specimen used in this experiment was tested at a strain rate of approximately 400/s and did not fail. The specimen was loaded to approximately 900 MPa, experienced very little plastic strain, and then was unloaded. There is a strong agreement between the experimental data and the assumed linear elastic behavior. This provides some validation of the modulus of elasticity calculated from the ultrasound measurements and indicates that the strain gage data accurately measures real material behavior.

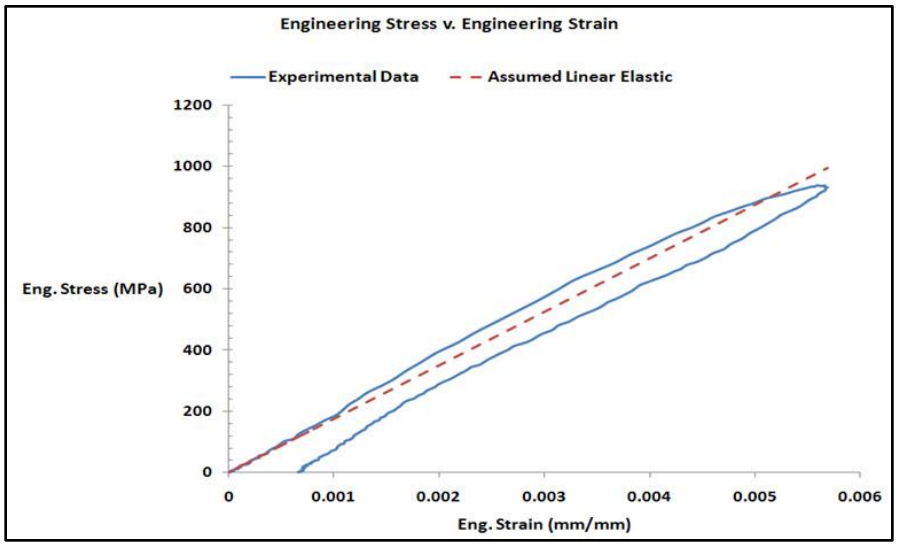

Figure 9. Stress–Strain curve from the third SHPB test. Strain is measured with a strain-gage mounted directly on the specimen.

The results from the fourth SHPB test are shown in figure 10. As in the previous test, initially the experimental stress strain curve strongly agrees with the theoretical calculation, but the values begin to differ at approximately 200 MPa. The slope of the experimental data still closely follows that of the assumed elastic behavior, particularly during elastic unloading.

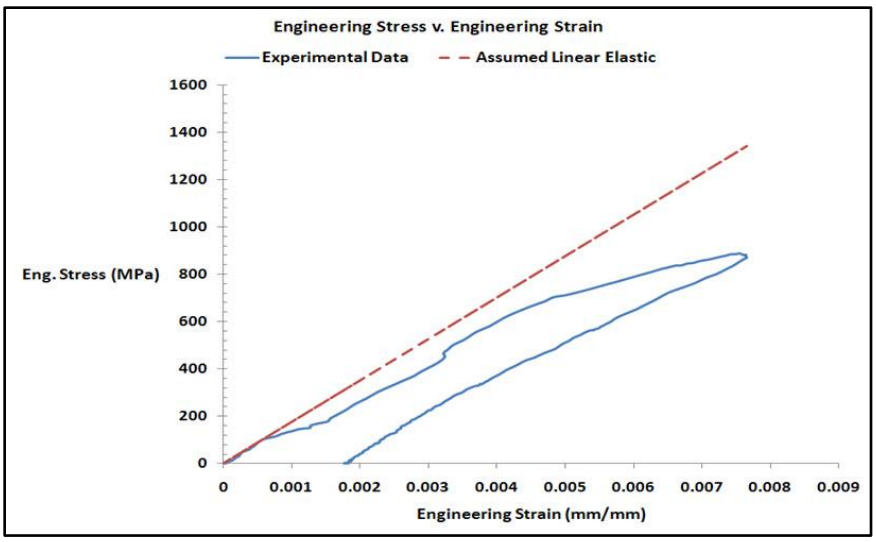

Figure 10. Stress–Strain curve from the fourth SHPB test. Strain is measured with a strain-gage mounted directly on the specimen.

Figure 11 shows the maximum engineering stresses for the SHPB tests. As was the case with the low rate experiments it was difficult to find an exact failure stress for the material. Whereas all the specimens tested at low rates failed, this was not the case for the high rate experiments. Maximum stresses are reported in figure 11 for samples that did not fail because they represent lower bounds for failure stresses. Table 4 lists the strain rates from the high rate experiments for which data was available. The dynamic nature of the tests combined with the brittleness of the material made it difficult to obtain accurate strain rate estimates for every test.

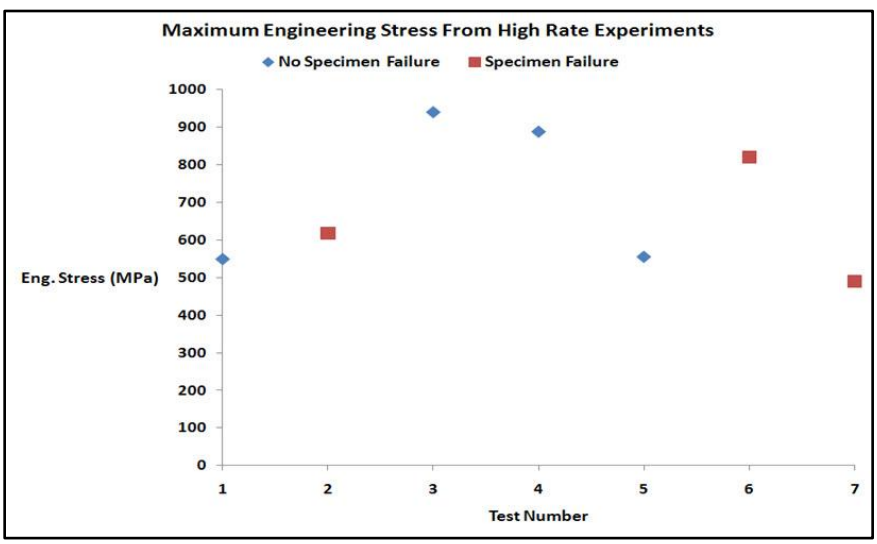

Figure 11. Blue points represent maximum stress for specimens that did not fail and represent lower bounds for failure stresses. Red points are failure stresses for specimens that did fail.

Table 4. Strain rates for dynamic compression tests.

Test Number	Strain Rate
	(1/s)
3	400
4	500
5	250

5. Conclusions

Data from compression tests on $TiAl_3$ have been presented. The results demonstrate a large amount of variability in failure stresses for these samples. The average low rate failure stress was 552 MPa with a standard deviation of 245 MPa. The average high rate failure stress was 642 MPa with a standard deviation of 166 MPa. This large variation is expected and due to the brittle nature of $TiAl_3$. It also suggests the presence of a wide range of defects in the specimens. These could be due to both material manufacturing (i.e., inherent to the material itself) and specimen fabrication (e.g., surface defects from machining). For this material it is unclear the relative contributions of each. Regardless, the variance in the data is representative of how the material behaves and should be considered in modeling efforts.

There were also difficulties in making small strain measurements for $TiAl_3$, i.e., inferring specimen strain from crosshead displacement and the standard SHPB analysis was not accurate. To improve these measurements, gages were bonded directly to specimens, and some stress-strain curves were obtained at both high and low rates. From these, it was seen that there was some differences between the elastic moduli measured from the compression experiments and that measured from ultrasound. Furthermore, the material behaved almost elastically, although some plastic deformation was observed.

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24	RDRL WMM B C RANDOW MAJ R HOWELL G GAZONAS M VANLANDINGHAM B CHEESEMAN RDRL WMP B D CASEM A DWIVEDI (2 HC) J BRADLEY (2 HC) C HOPPEL S BILYK T WEERASOORIYA B LOVE M SCHEIDLER D DANDEKAR RDRL WMM D E CHIN RDRL WMP D R DONEY D KLEPONIS J RUNYEON RDRL WMP E D HACKBARTH M BURKINS S BARTUS RDRL SLB A B WARD

INTENTIONALLY LEFT BLANK.