Test and Simulation Comparison using Titanium Material Models based on MAT224

Leyu Wang[1)], Filippo Dicecca[2)], Sean Haight[1)], Kelly Carney[1)], Paul DuBois[1)], William Emmerling[3)], Cing-Dao Kan[1)]

[1]Center of Collision Safety and Analysis, George Mason University, USA
[2]Transport System Safety Lab, Department of Aerospace Science and Technology, Politecnico di Milano, Italy
[3]Federal Aviation Administration, USA

Abstract

*Titanium plate impact tests are simulated with *MAT_224, an elasto-visco-plastic material model in LS-DYNA® with tabulated stress versus strain curves as well as tabulated strain rate and temperature dependency. The *MAT_224 input deck is built upon a series of tensile, shear and compression tests at different strain rates and temperatures conducted on a 0.5" commercial off-the-shelf titanium plate. The input of *MAT_224 is generated so that it predicts all the material property tests conducted on this plate. The 0.5" plate titanium *MAT_224 model is later used to simulate the 0.5" plate impact tests as well as impact tests of the 0.09", 0.14" and 0.25" plates. The predictive performance of the material model for each plate, including exit velocity, failure mode and the profile of the intrusion, are evaluated using the test results. It is shown that the 0.5" plate Ti-6Al-4V *MAT_224 predicts the impact test of the 0.5" titanium plate with great accuracy. However, the predictions for the impact tests of the 0.09", 0.14" and 0.25" plates, using the same material model, are not as accurate. All of these plates meet the specification of AMS-4911, but vary in yield stress from the 0.5" plate, as well as varying between states and material direction. The 0.5 inch plate is the most isotropic and as such most suited for a Von Mises material model. The other plates are from different lots, and clearly have had different processing to produce thinner material thickness. These differences within the same specification are thought to be the cause of the larger difference between test and simulation of the other plates.*

Introduction

Impact simulation of structures with titanium alloy plays an important role in various industrial applications. The predictive capability of the simulation largely depends on the quality of the material and failure model. Traditionally the Johnson-Cook model has been used to simulate strain rate and temperature dependent materials[1–3]. Although successful in individual cases, Johnson Cook model is highly dependent on the choice of parameters. Accurate predictions of different test conditions often result in different Johnson-Cook parameters for the same material. For example, one set of parameters often only allows fitting the experimental data for a particular plate thickness. In other words, the number of degrees of freedom embedded in the Johnson-Cook analytical model is not sufficient to capture the physical reality of the material (i.e. fit a wide range of experimental setups). In addition, it has been noticed [4,5] that the plastic failure strain of Ti-6Al-4V is dependent upon the 3D state of the stress, which can be characterized by two invariants of the stress tensor (triaxiality and Lode parameter). In the Johnson-Cook material model, the failure strain is only dependent upon the triaxiality. To expand the usefulness of the Johnson-Cook model to predict differing failure modes with a single material model input, *MAT_224 was introduced into LS-DYNA as a tabulated generalization of the original Johnson-Cook model. In *MAT_224, the failure strain is dependent upon triaxiality and Lode parameter. This allows for a complex failure surface defined by the state of stress. The fully tabulated input of *MAT_224 allows more degrees of freedom than the original parameterized formulation, enabling an accurate fit for all material property tests at different strain rate, temperature and state of stress[5,6]. To develop a *MAT_224 material model for titanium, a commercial off-the-shelf 0.5" Ti-6Al-4V plate was used for material property testing. All of the testing of the 0.5” plate came from a single plate of titanium, so the mechanical property testing and ballistic impact testing used the same exact material. Ballistic testing was performed on three other Ti-6Al-4V plates with same temper and within the AMS-4911 specification (with thicknesses of 0.09", 0.14" and 0.25"); however the four plates described in this paper have varying mechanical properties.

The performance of the 0.5" Ti-6Al-4V material model was evaluated by simulating a series of impact tests on 0.5" plates[7]. These tests have the identical test conditions except for the varying initial velocity of the impactors. The predicted exit velocity, failure mode and the deformation contour are compared with the experimental data and an analytical formula for calculating residual velocity above the ballistic limit[9]. The 0.5" Ti6Al4V *MAT_224 model is also used in the simulations of 0.09", 0.14" and 0.25" plate impact tests in order to study the predictive capability of a material model, based on the mechanical properties of one plate, in the impact simulation of different plates.

Material Model Development of 0.5" Ti-6Al-4V Plate with *MAT_224

A single commercial off-the-shelf 0.5" thickness Ti-6Al-4V AMS-4911plate[5] was used to create specimens that were tested under different loading conditions. All test specimens were cut from the same 0.5"plate and which was also later used for the 0.5" impact tests[7]. There were more than 20 mechanical property tests with different shapes and loading conditions. Among them are quasi-static and dynamic tests in tension, compression, torsion, and punch. Tension tests are also performed with different material orientations of the plate. In addition, failure tests under different states of stress were used to populate the failure surface. (c.f. Figure 1)

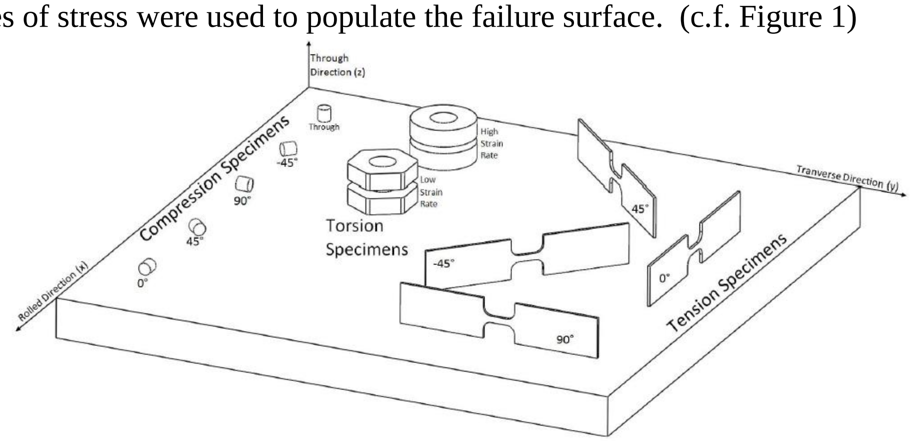

Figure 1 Specimen manufacturing orientations for the 12.7mm plate stock[8]

The process of building the *MAT_224 material model input is largely a reverse engineering procedure based on trial and error. A material curve or table is first assumed and used in a simulation to see if the result is close enough to the material test. Both force displacement response and DIC images of the strain field are used for judging the accuracy of the simulation. This process continues until the material model input gives results that are close enough to the test for all experiments. Failure test specimens were carefully designed to generate a state of stress corresponding to desired values of triaxiality and Lode parameter (c.f. Figure 2). For states of stress that are outside the range covered by material testing, the user must extrapolate based on existing data. The detailed procedure was documented in an FAA report[5]. The end result is a single *MAT_224 input deck with 46 load curves and 3 tables. This input deck accurately reproduces all material tests and is regularized for element sizes between of 0.1 mm and 0.5 mm.

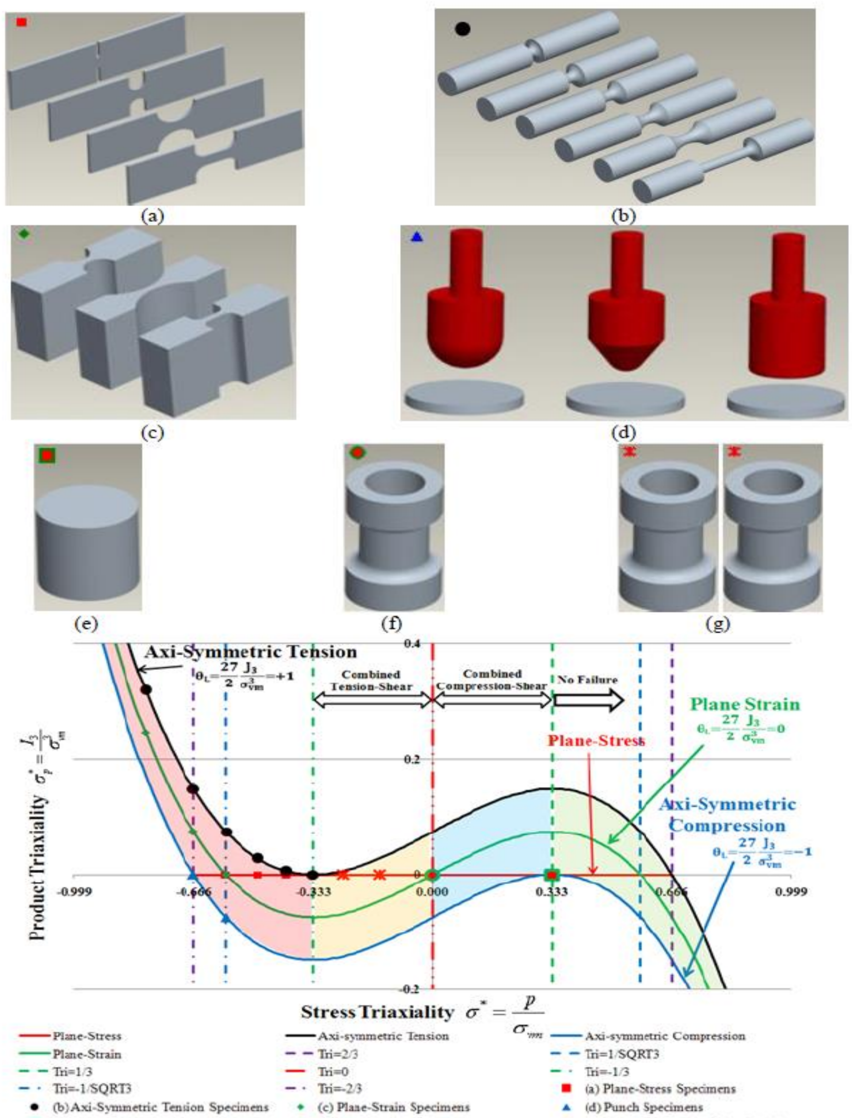

Figure 2 The specimen used to determined failure strain of different triaxility and Lode parameter[4]

0.5" Ti6Al4V *MAT_224 Model Used in the 0.5" Plate Impact Simulation

To test the predictive capability of the titanium model, impact simulation results produced with the 0.5" *MAT_224 model are compared with the physical test results of the exact same material plate[5,7]. A cylindrical projectile made from A2 Tool steel was shot into a Ti-6Al-4V plate (c.f. Figure 3). The initial and exit velocities of the projectile, the failure mode and the deformation contour of the plate are measured and compared with the simulation. It was observed that the projectile had no plastic deformation after impact. Thus *MAT_ELASTIC was used to model the projectile material (c.f. Figure 4). Note that the projectile has a slightly rounded top and the impact angle is not always perpendicular to the plate. It will be shown that those two factors have an influence on the simulation results.

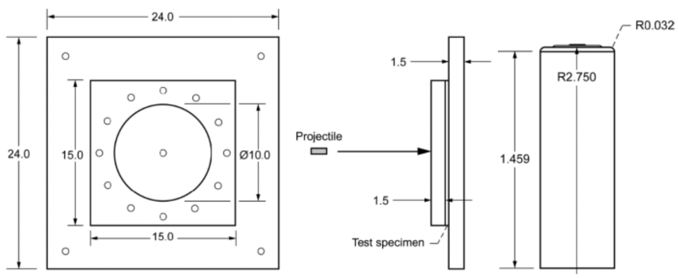

Figure 3 Design Geometry for NASA Ballistic Plate Test Setup (left and center), and Projectile (right)[7]

```
*KEYWORD
*MAT_ELASTIC
$#     mid         ro         e        pr
         3 7.8600E-6  190.0000   0.32000
```

Figure 4 material card of the projectile[5]

The plate was modeled with 8 node hexahedral, constant stress solid elements (elform=1). A uniform square mesh pattern was used in the impact area. A comparative study has shown that for different mesh patterns, using approximately the same element size, the simulation results show slightly difference exit velocities. A perfect square pattern is chosen because it is unbiased toward circular element erosion patterns.

The default LS-DYNA hourglass control method was not sufficient due to the excessive rates of deformation. The hourglass control method 6 was chosen after a comparative study of different hourglass methods was performed. With ihq=6 being used, the hourglass energy is less than 1% of the internal energy for all simulations presented in this paper.

The residual velocity is plotted as a function of initial velocity as shown in Figure 5. It is noted that the simulation captures ballistic limit of the test (187 m/s). The test and simulation also show a close match of the exit velocities. An analytical formula[9] is used to show the trend of exit velocity vs. initial velocity:

$$V_r = \frac{1}{1+\lambda}\sqrt{V_0^2 - V_{bl}^2} \tag{1.1}$$

$$\lambda = \frac{m}{M} = \frac{\rho_t H}{\rho_p L_{eff}} V_r \tag{1.2}$$

where V_r is the residual velocity of the projectile, V_0 is the initial velocity of the projectile,

V_{bl} is the ballistic limit of the projectile, m is the mass of the plug and M is the mass of the projectile. ρ_t is the density of plate(target) and ρ_p is the density of the projectile, H is the thickness of the plate, L_{eff} is the effective length of the projectile. It is shown that the analytical formula is not as accurate as the simulation prediction (c.f. Figure 5).

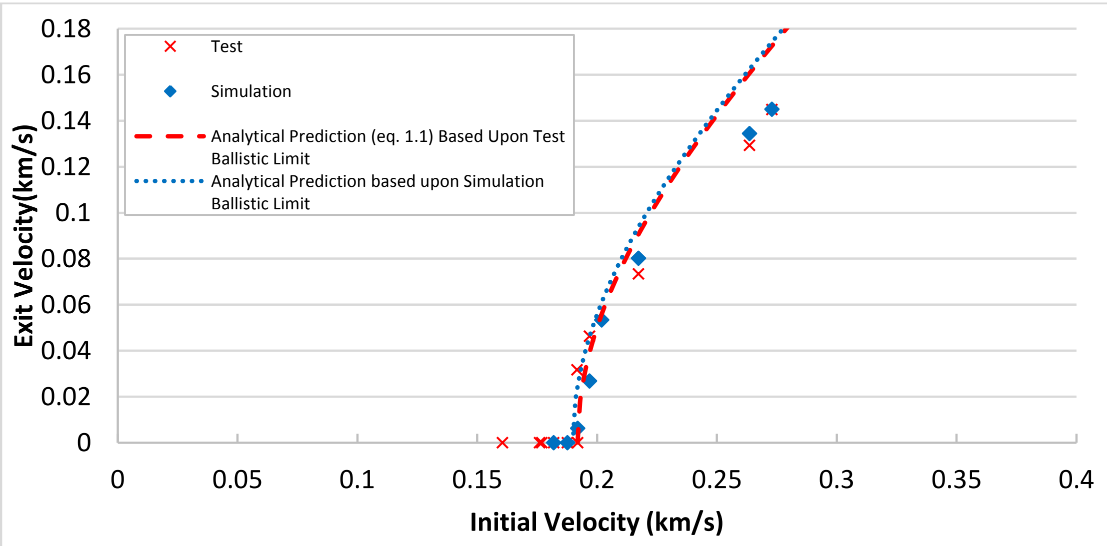

Figure 5 Test Data and Simulation Results for 0.5" plate Ballistic Impact Tests[5]

Further comparison indicates that the simulation also replicates the deformation contour for the case where the projectile does not penetrate the plate (c.f. Figure 6). The failure mode of the simulation is also close to that of the test (but not exact). To conclude, 0.5" Ti-6Al-4V *MAT_224 material model is able to accurately predict the plate impact test of 0.5"plate.

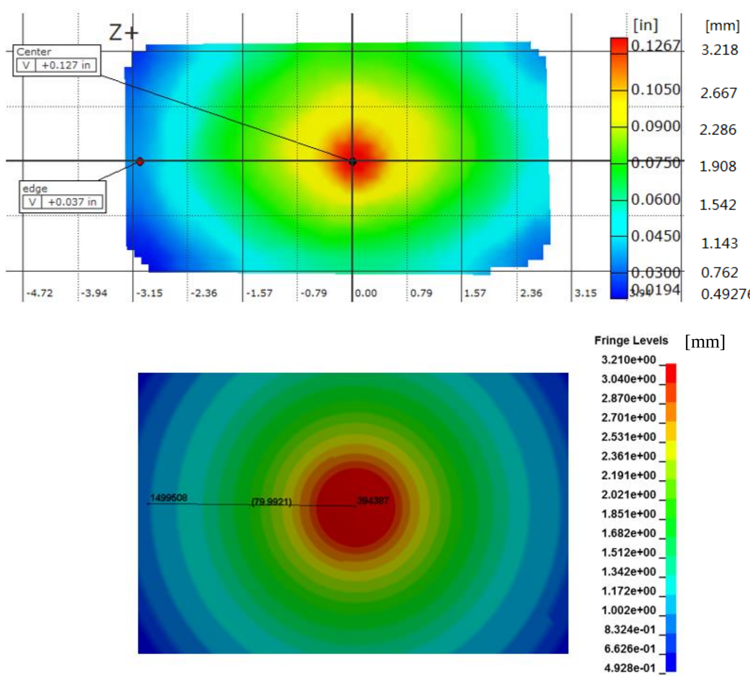

Figure 6 Plots Showing Center Displacement Measured (above) and Simulated(below)[5]

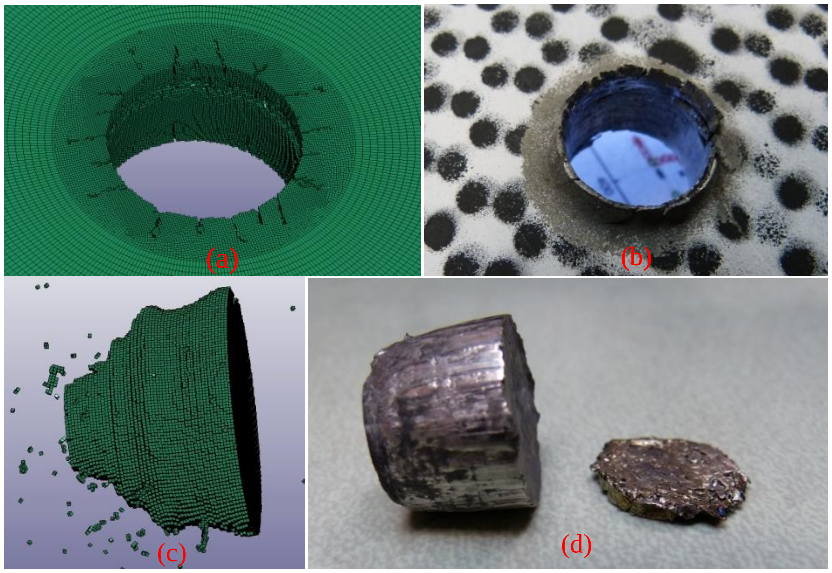

Figure 7 The comparison of the plugging shape for 0.5" plate test and simulation (DB178 with the initial velocity of 865ft/s) (a) back side of the plate in the simulation (b) back side of the plate in the test[7]. (c)side view of the plugging in the simulation (d) side view of the plug in the test[7].

0.5" Ti6Al4V *MAT_224 Model Used in the 0.25" Plate Impact Simulation

The 0.25" plate impact tests are also simulated with the 0.5" Ti-6Al-4V *MAT_224 material model to evaluate the envelope of the effectiveness of the material model. A tensile test comparison (c.f. Figure 8) has shown that the material of the 0.5" plate is stronger than the material of 0.25" at all strain rates that were tested. Therefore the 0.5" *MAT_224 model will overestimate the strength of the material when used in the simulation of 0.25" plate.

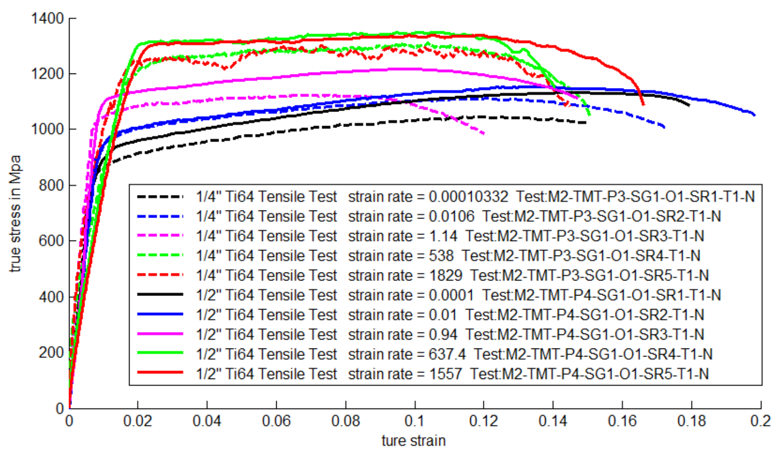

Figure 8 Stress strain relation of different strain rate for 0.25" and 0.5" Ti6Al4V plate

The physical impact test of 0.25" plate has the same set-up as the 0.5" test except for the projectile length. The identical mesh size and pattern are used in both 0.25" plate and 0.5"simulation, but because of the thinner plate there are fewer total elements. The projectile mass and impact angle in the simulations replicate the test. The lowest penetrating velocity of the test is 216.4 (m/s) whereas the ballistic limit in the simulation corresponds to 259.6 (m/s). (c.f.

Figure 9) Remember that the material strength in the simulation overestimates the material strength; the 0.5" titanium plate is stronger than the material of the 0.25" plate (c.f. Figure 8). Therefore, the expected trend of an overestimate of the material strength leading to an overestimate of the ballistic limit is fulfilled.

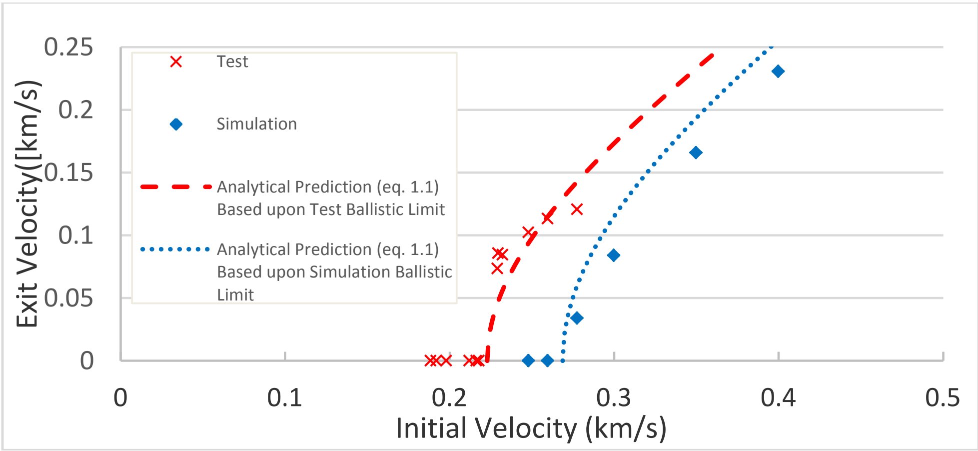

Figure 9 0.25" Titanium Plate Impact Test Compare with the Simulation using 0.5" material model.

It is also worthwhile to mention that both the test results and the simulation results follow the analytical formula[9] that determines the residual velocity of blunt shaped cylinder projectiles (c.f. Figure 9). Both result trends are dependent on the varying ballistic limit, as shown in Equation (1.1). So, if the differing ballistic limit is considered, the trend of the exit velocities is a good match.

To study the failure mode, the contained case with highest velocity in the physical test is compared with the contained case with highest velocity in the simulation. As shown in Figure 10, the physical test has a cylindrical plug, which indicates the occurrence of an adiabatic shear band. In the simulation, the failure starts from both front and back of the plate and subsequently is joined together in the middle, forming a plug with a conical shape (c.f. Figure 10), similar to but not quite as close a match as the 0.5” plate simulation to test.

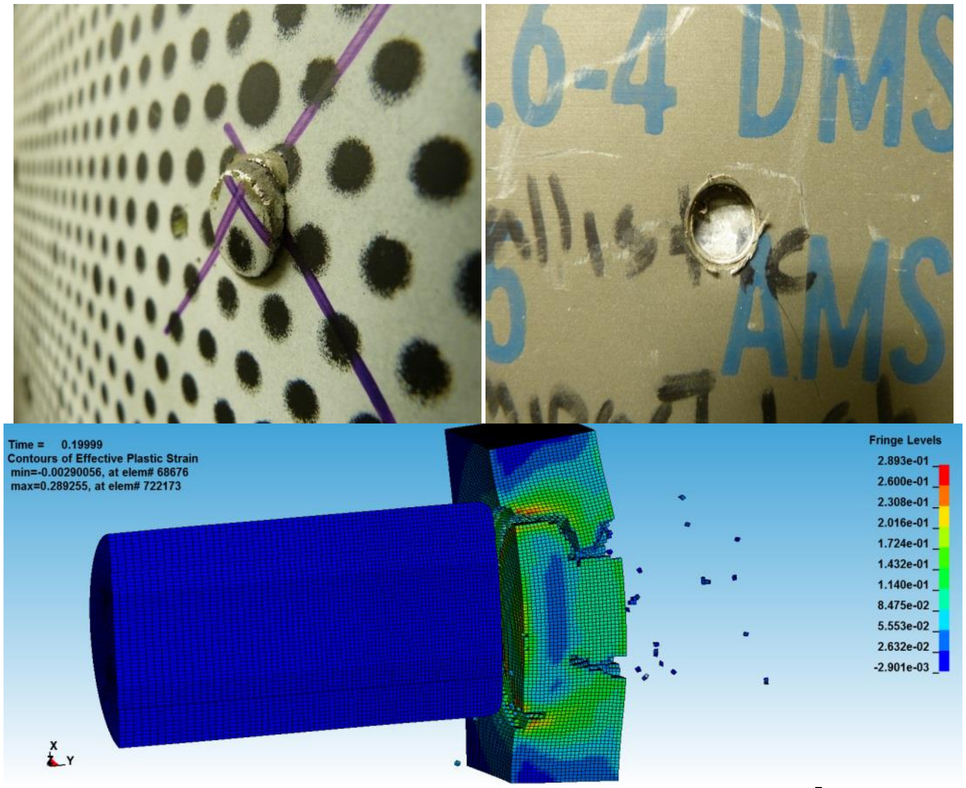

Figure 10 (Top Left) Photo of the back side of 0.25" Titanium Plate after impact test 0.25" [7], (Top Right) Photo of the front side of 0.25" Titanium Plate after impact test 0.25" [7], (Bottom) 0.25" Titanium Plate Impact Simulation using 0.5" material model.

To conclude, the *MAT_224 model developed from 0.5" Ti-6Al-4V plate does not replicate the impact test of 0.25" Ti-6Al-4V plate. The greatest difference between the simulation and the test can be understood by considering the measured difference in yield stress between the material model and the 0.25" plate. The predicted ballistic limit is 20% higher than the physical test, consistent with the difference in material properties. The simulation was an approximate match to the correct failure mode, as in the 0.5" plate simulations.

0.5" Ti6Al4V MAT224 Model Used in 0.09" Plate Impact Simulation

The impact test set-up for the 0.09" plate is similar to that of the 0.5" and 0.25" plate except for the projectile dimension, and significantly, the projectile material. The projectile in 0.09" plate is made out of annealed Ti-6Al-4V with the heat treatment AMS 2928[7]. Note that the annealed Ti-6Al-4V is softer than Ti-6Al-4V AMS-4911(c.f. Figure 11). The yield strength, Poisson's ratio and the tangent modulus are different. It was observed that the projectile had some plastic deformation after impact[7]. A simple material model is built with *MAT_024 based on the average of mechanical properties obtained from the literature (c.f. Figure 11) [10–14]. The predicted deformation of the projectile after impact is compared between to the (c.f. Figure 22)

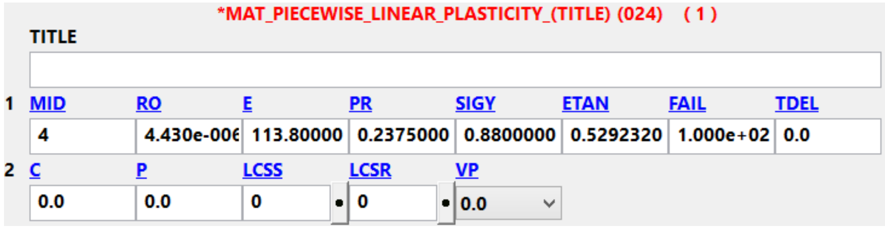

Figure 11 Annealed Ti6Al4V AMS 2928 model

A sub-set of high strain rate tensile tests were performed on 0.09" plate in order to compare the difference in mechanical properties between the 0.09" and the 0.5" plate. It is seen that the yield stress of the 0.09" plate is lower than that of the 0.5" plate for the strain rates that were tested (c.f. Figure 12). Therefore, just as in the simulation of 0.25" plate, the 0.5" *MAT_224 model will overestimate the strength of the material when used in the simulation of 0.09" plate.

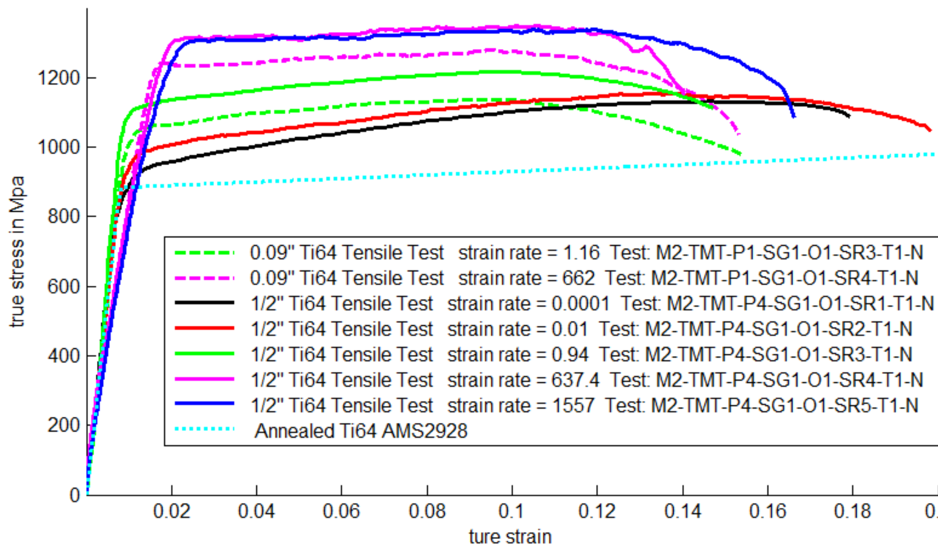

Figure 12 Stress Strain Relation of 0.09" Ti6Al4V plate compared with 0.5" Ti6Al4V and Annealed Ti6Al4V

Both the initial velocity and the impact angle influence the residual velocity[7]. The impact angle is the angle between the axis of the cylindrical projectile and the normal direction to the panel at the moment of impact. A comparison with two cases has shown that the simulations with identical initial velocity but different impact angles have different exit velocities (c.f. Table 1).

Impact Velocity 180 (m/s)	0 deg	0.9 deg	4.4 deg	4.5 deg	5.1 deg
Exit Velocity (m/s)	0	0	7.5	6.8	8.5

Impact Velocity 185 (m/s)	0 deg	2 deg	4 deg	6 deg	8 deg
Exit Velocity (m/s)	14.68	21.3	18	17	14.72

Table 1 The influence of impact angle to exit velocity in simulations

The pictures below (c.f. Figure 13-Figure 14) show how much the failure mode and the exit velocity can change due to a different impact angle with the same impact velocity. In Figure 13, ballistic impact simulations at 170 (m/s) with 0 degree impact angle and 4.4 degree impact angle are shown. In 0 degree impact angle, there is a clear circular cut with plugging whereas in the 4.4 degree impact angle, the plate failed by plugging and petaling with two main cracks. The projectile is contained in both cases.

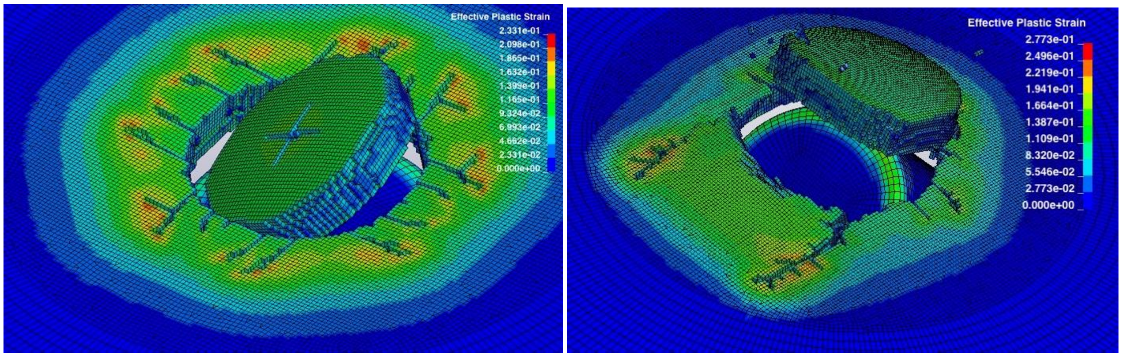

Figure 13 0.09" Failure mode and exit velocity comparison between 0 deg impact angle (left) and 4.4 deg impact angle (right) at 170m/s impact velocity

In Figure 14, ballistic impacts at 180 (m/s) with 0 degree impact angle and 4.4 degree impact angle are shown. In the 0 degree impact angle case, there is a clear circular cut with plug releasing whereas in the 4.4 degree impact angle, the plate failed by plugging and petaling. In addition, in the 0 degree impact angle case the projectile is contained instead of a 7.5 (m/s) exit velocity in the other case of 4.4 degree impact angle.

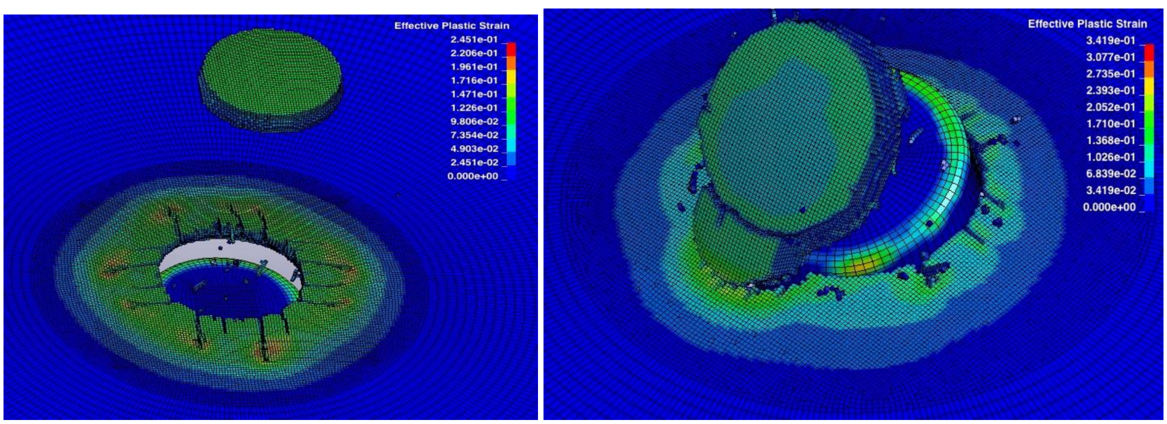

Figure 14 0.09" Failure mode and exit velocity comparison between 0 deg impact angle (left) and 4.4 deg impact angle (right) at 180 m/s impact velocity

Similar results are obtained with the experimental tests as shown in the Figure 15, It is observed that the petaling mode is common for both tests and simulation with large impact angle.

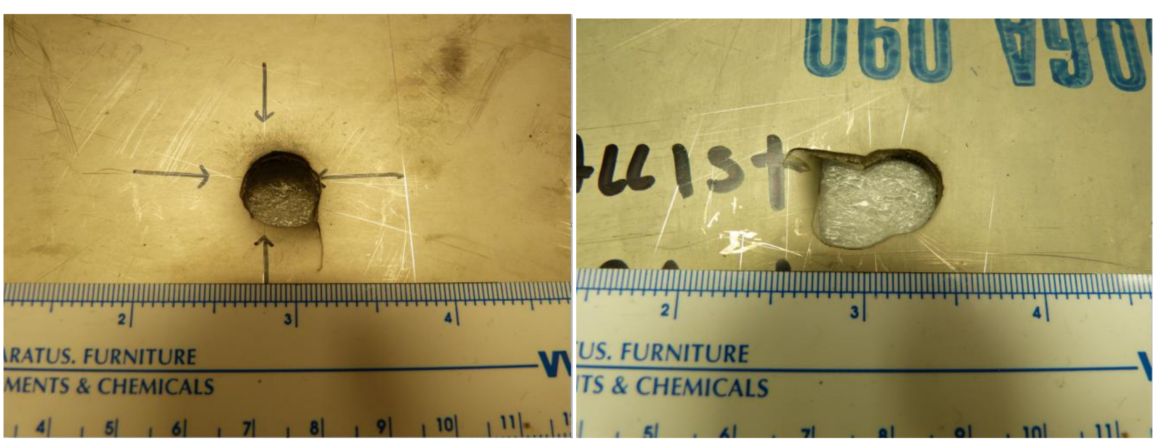

Figure 15 Failure mode and exit velocity comparison between 2.4 deg impact angle(Test # DB137 with initial velocity of 237 m/s) (left) and 6.0 deg impact angle (Test # DB130 with initial velocity of 233 m/s (right) [7]

In the case with 185 (m/s) impact velocities, the exit velocity with 0 degree impact angle and 8 degree impact angle are similar because in the later case, the projectile bounces inside the penetrated hole, causing more kinetic energy absorption.

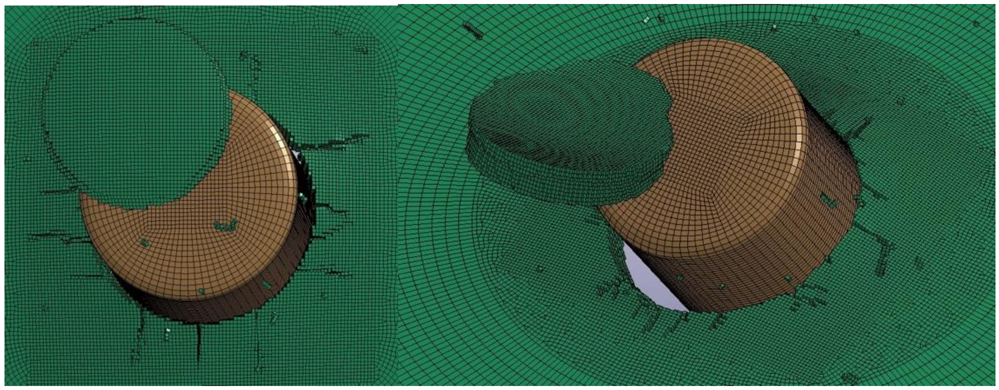

Figure 16 0.09" Failure mode and exit velocity comparison between 0 deg impact angle (left) and 8 deg impact angle (right) at 185 m/s impact velocity

All impact tests of this work were simulated with the exact geometry, mass and impact angle. Because the impact angle varies case by case in the test, the simulation exit velocity does not follow a smooth line.

The simulation exit velocities of the projectiles are compared with the exit velocities of the test. The simulation predicts a ballistic limit of 180 (m/s) whereas the test has a ballistic limit of 219 (m/s). (c.f. Figure 17). This is not consistent with the expectation that the overestimate of the material properties of the 0.09" plate would cause the predicted ballisitic limit to be higher than the test ballistic limit.

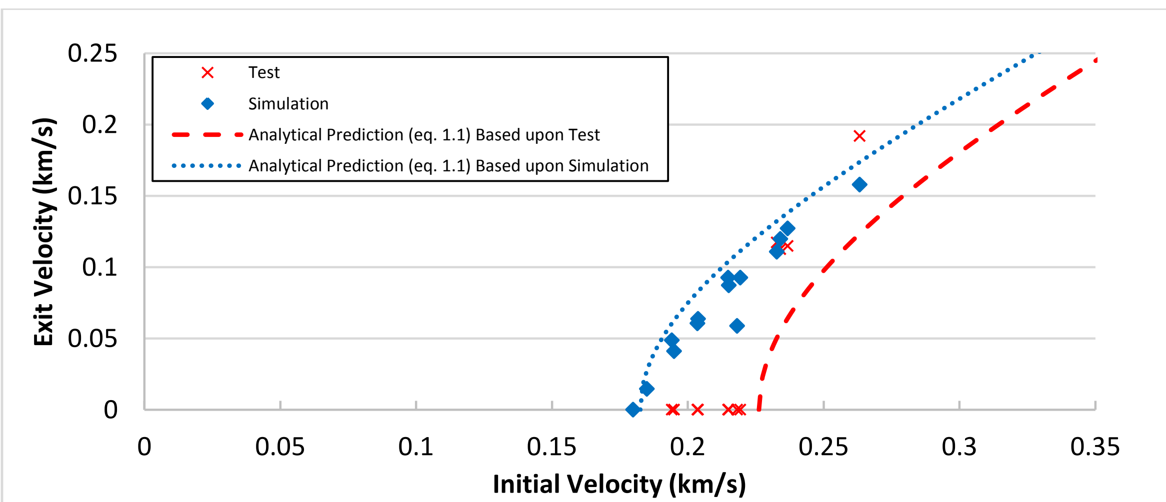

Figure 17 0.09" Titanium Plate Impact Test Compare with the Simulation using 0.5" material model.

Notice that there is also a mismatch of the exit velocity trend between the simulations and the physical tests (c.f. Figure 17). It is also very interesting to note that the simulations follow the analytical formula given in Equation 1.1, while the test exit velocities do not. Therefore, the simulations appear to be predicting a failure mode assumed by the analytical expression, but which did not occur in the actual tests.

In the simulation, the plate failed by plugging and petaling with some subsequent, limited crack propagation. In the physical test, the plate failed by petaling and subsequent, longer crack propagation. Notice that the crack in the physical test (c.f. Figure 18) is several times the length of the projectile's diameter. The failure mode appears to be similar to fracture, as seen in the rough surface in Figure 18. In fact, the crack propagation appears to be the dominant failure mode when the initial velocities are slightly greater than the ballistic limit. For higher impact velocities, the simulations predict a failure mode with plugging that is similar to the test (c.f. Figure 19).

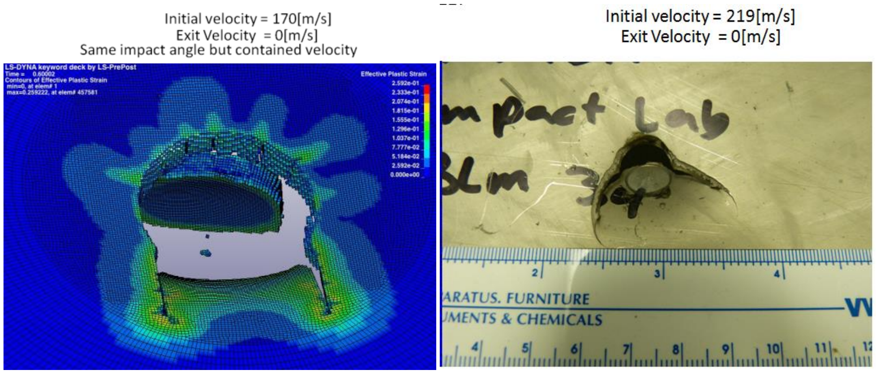

Figure 18 0.09" Failure model comparison between the simulation(left) and physical test[7] (right) for lower velocity cases "DB127"

Figure 19 0.09" Failure model comparison between the simulation(left) and physical test [7] (right) for higher velocity cases "DB132"

To conclude, the 0.5" *MAT_224 does not predict the impact test of the 0.09" plate very well. The ballistic limit of the simulation is 18% lower than the physical test, while the yield stress of the 0.5" Ti-6Al-4V *MAT_224 model is greater than the yield stress of the titanium in the 0.09" plate. The underestimation of the simulation ballistic limit might be attributed to the failure mode mismatch. The test shows plugging at high velocity impact and fracture and petaling at low velocity impact. The simulation only matches the failure mode at high velocity. Also note that the exit velocity trend in the simulations does not match the trend observed in the test, even when correcting for the difference in ballistic limit. Considering that the simulations match the theoretical formula, while the test exit velocities do not, this mismatch could also be attributed to the failure mode mismatch.

0.5" Ti6Al4V MAT224 Model used in 0.14" plate Impact Simulation

Tensile tests on samples from the 0.14" Ti-6Al-4V plate and the 0.5" Ti-6Al-4V plate are compared in Figure 20. As in the 0.09” and the 0.25” plates, it is seen that the 0.5" plate is stronger than 0.14" plate for the similar strain rates that were tested using material from plates of both thickness.

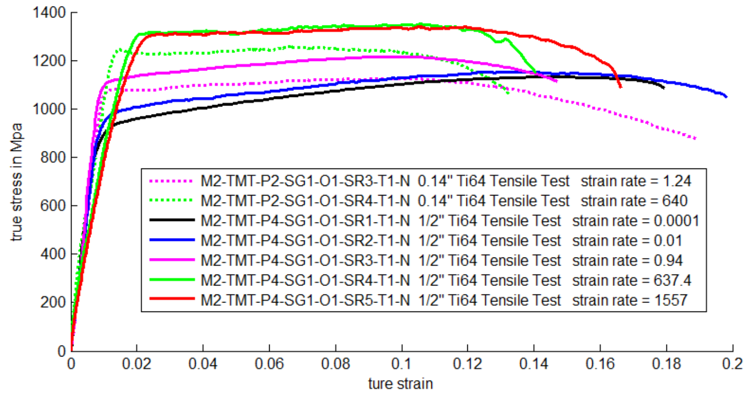

Figure 20 Stress Strain Relation of 0.14" and 0.5" plate under different strain rate.

The impact test on the 0.14" plate has the same setup as the 0.09" plate experiments except for the length dimension of the projectile. The projectile is made of the same annealed titanium used in the 0.09 testing. The projectile material card in the 0.14" plate impact simulation is identical to that of the 0.09" plate. The *MAT_224 0.5" model is used to model the plate. In the impact simulation, the material model overestimates the strength of 0.14" plate, as in the 0.09” and 0.25” simulations. The simulation predicts a ballistic limit of 247(m/s) compared to the ballistic limit of 231 (m/s) in the physical test (6.9% error) (c.f. Figure 21). This difference could be expected, based upon the difference in material properties between the model and the actual plate. Here it is interesting to note that the exit velocity trend of the simulation, when considering the mismatch of the ballistic limit, matches the exit velocity trend of the tests reasonably well.

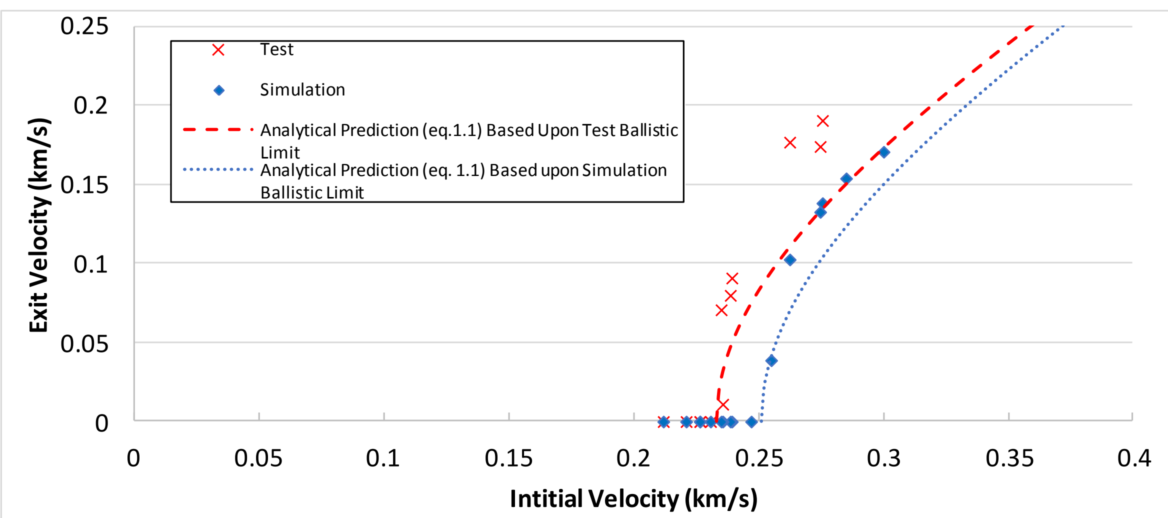

Figure 21 0.14" Titanium Plate Impact Test Compare with the Simulation using 0.5" material model.

There is a good correlation of projectile's plastic deformation between test and simulation.(c.f. Figure 22)

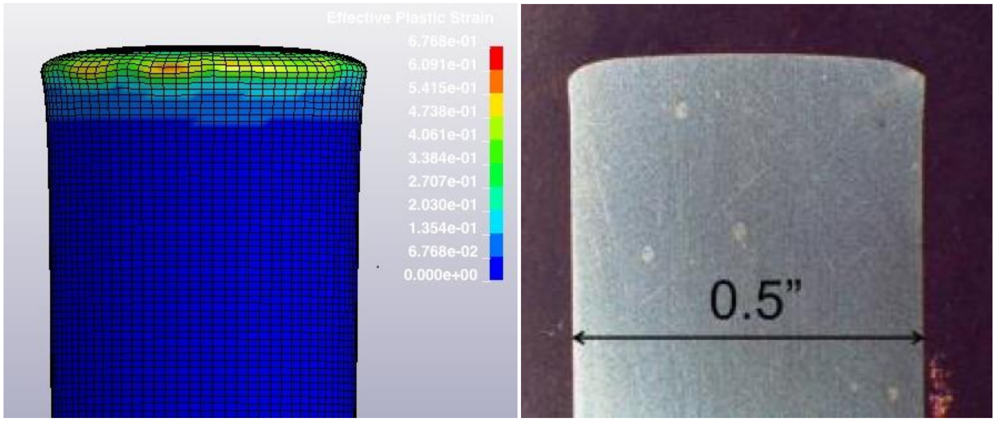

Figure 22 Extensive plastic deformation in annealed Titanium projectile for the simulation(left) and test(right)

The failure mode is compared between the test and simulation for the contained case (c.f. Figure 23). The failure pattern is similar, but not exact.

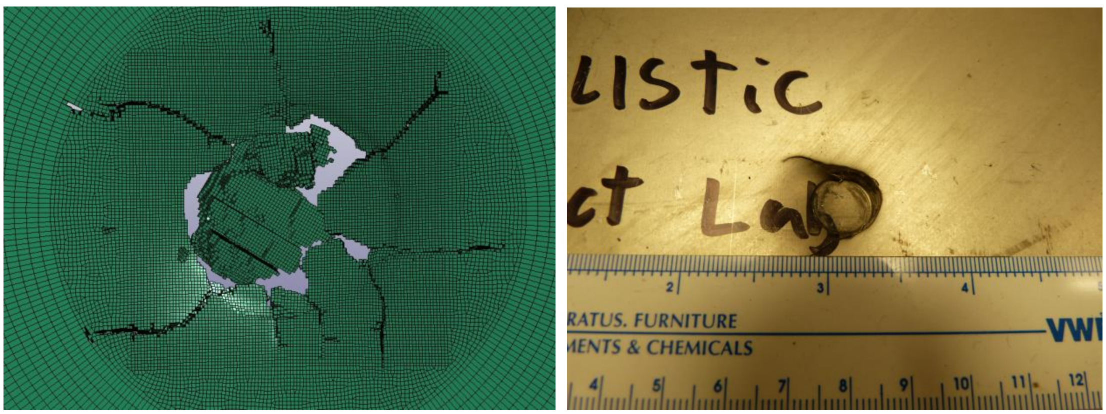

Figure 23 0.14" Titanium Plate Impact Test Compare with the Simulation using 0.5" material model. Simulation # DB147 with initial velocity 239m/s and exit velocity 0 m/s(left). Test # DB144 with initial velocity 221 (m/s) and exit velocity 0 (m/s) (right) [7]

Summary and Discussion

*MAT_224, a fully tabulated LS-DYNA material card with strain rate, temperature and failure surface dependency, was used to build a material model for a commercial, off-the-shelf 0.5" Ti-6Al-4V plate. Simulation results of impact tests on Ti-6Al-4V plates with 0.5", 0.25", 0.14" and 0.09" thickness were compared with ballistic test[7] results. The 0.5" Ti-6Al-4V *MAT_224 model successfully predicts the impact test of 0.5" titanium plate. The simulations capture the ballistic limit, the exit velocity for the penetrated cases, deformation shape of the contained cases as well as the failure mode.

The 0.5" Ti6Al4V MAT224 overestimates the ballistic limit velocity of the 0.14" and the 0.25" plates, consistent with the difference in yield stresses between the 0.5” plate and the thinner plates. Taking into account the difference in ballistic limit, the predicted exit velocity trends also are a good match to the test exit velocity trends. The failure modes in these thicknesses are also a reasonable match.

With the 0.09” plate, the ballistic limit is underestimated (inconsistent with the expectation based upon the overestimate of the yield strength); the exit velocity trend does not match the test, and the failure modes do not match. The 0.09" plate exhibited a large 45 degree crack propagating away from the initial impact. The condition which caused the crack to run away from the impact area out into the plate is not simulated with *MAT_224. So while the differences in yield stresses can explain the differences observed between the impact predictions of the 0.25" and the 0.14" plates and the actual tests, there is a more fundamental difference between the 0.09" simulations and the 0.09" tests.

All of these plates meet the specification of AMS-4911, but vary in yield stress both between states of stress and directions in the material. The 0.5 inch plate is the most isotropic and as such most suited for a Von Mises material model. The other plates are from different lots, and clearly have had different processing to produce thinner material thickness. These differences within the same specification are thought to be the cause of the larger difference between test and simulation of the other plates.

Fragment impact predictability is sensitive to the actual mechanical properties in the test specimen. Care should be taken to develop *MAT_224 models from a single material plate so that there are no plate to plate material differences accidentally included in the material model.

Future work should investigate orthotropic affects and how they may affect the morphology of failure. Further, the failure surface may be able to be shifted to the actual material properties to improve accuracy. Finally additional failure characterization tests are desirable to increase the population across the failure surface and improve the fidelity.

Acknowledgment

This research was supported by Federal Aviation Administration(FAA). We thank our colleagues from FAA, Ohio State University, NASA, George Mason University, Politecnico di Milano who provided insight and expertise that greatly assisted the research.

We thank, Mike Pereira, Jeremy Seidt, Chung-Kyu Park, Stefano Dolci for assistance with the test and simulations.

References

1. Calamaz, M., Coupard, D. & Girot, F. A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti–6Al–4V. *Int. J. Mach. Tools Manuf.* **48,** 275–288 (2008).
2. Kay, G. *Failure modeling of titanium 6AI-4V and aluminum 2024-T3 with the Johnson-Cook material model*. (Office of Aviation Research, Federal Aviation Administration, 2003).

3. Meyer, H. W. & Kleponis, D. S. Modeling the high strain rate behavior of titanium undergoing ballistic impact and penetration. *Int. J. Impact Eng.* **26,** 509–521 (2001).
4. Buyuk, M. Development of A Tabulated Thermo-Viscoplastic Material Model with Regularized Failure for Dynamic Ductile Failure Prediction of Structures under Impact Loading. (THE GEORGE WASHINGTON UNIVERSITY, 2013).
5. Sean Haight, Leyu Wang, Paul Du Bois, Kelly Carney, Cing-Dao Kan. Development of a Titanium Alloy Ti-6Al-4V Material Model Used in LS-DYNA. DOT/FAA/In Preparation (2015).
6. Buyuk, M. Development of a New Metal Material Model in LS-DYNA Part 2: Development of A Tabulated Thermo-Viscoplastic Material Model With Regularized Failure for Dynamic Ductile Failure Prediction of Structures Under Impact Loading. DOT/FAA/TC-13/25, P2 (2014).
7. Pereira, J. M., Revilock, D. M., Lerch, B. A. & Ruggeri, C. R. Impact testing of aluminum 2024 and titanium 6AL-4V for material model development. *DOT/FAA/TC–12/58* **NASA/TM—2013-217869,** (2013).
8. Hammer, J. T. Plastic deformation and ductile fracture of Ti-6Al-4V under various loading conditions. (The Ohio State University, 2012).
9. Rosenberg, Z. & Dekel, E. *Terminal Ballistics*. (Springer Berlin Heidelberg, 2012).
10. ASM. ASM Material Data Sheet. (2016).
11. Veridiam. Titanium Alloy Ti 6AL-4V. (2016). Available at: http://www.veridiam.com/pdf/DataSheetTitaniumAlloy.pdf. (Accessed: 26th February 2016)
12. CRP Meccanica. Machining Titanium Alloys Ti-6AL4V. *CRP Meccanica. CNC Machining Company* (2016). Available at: http://www.crpmeccanica.com/machining-titanium-ti-6al4v/. (Accessed: 26th February 2016)

13. aircraftmaterials.com. Titanium Alloy Grade 5 / Ti 6Al-4V - Aircraft Materials. (2016). Available at: http://www.aircraftmaterials.com/data/titanium/ti6al4v.html. (Accessed: 26th February 2016)
14. Performance Titanium Group. Titanium Specification AMS 4928. (2016). Available at: http://performancetitanium.com/ams-4928/?gclid=CjwKEAiAuKy1BRCY5bTuvPeopXcSJAAq4OVs-lsJSz8d8xZiLwmkb2Tz0we4DvQM3FyGgesHLnOSHxoCydLw_wcB. (Accessed: 26th February 2016)