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An Evaluation of MAT_224 for Simulation of Impact and Failure Part 1: A Scaling Approach for Modeling AMS 4911 Titanium Plates With Different Thicknesses and Properties

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16. Abstract

The George Washington University, Ohio State University, NASA Glenn Research Center, and the FAA Aircraft Catastrophic Failure Prevention Program are working together to support the FAA initiative on certification by analysis. Predictive material modeling is demonstrated by having analytical predictions of the same condition match the observed test results. To match a test, the analytical model needs to match the actual plate material property, not the Metallic Material Properties Development and Standardization design or similar specifications. Titanium alloy (Ti-6Al-4V) with the same American Society for Metals specification, but with different processing and plate thicknesses, has varying mechanical properties. Any plates not from the same batch—including those from different suppliers and of different processing and thicknesses—have within-specification differences. Ideally, each plate thickness with different material properties needs to be treated as a new material, which requires a complete set of material tests to develop the constitutive model. Practically, such tests are expensive and time consuming. It is necessary to find a simple method to use the material model based on one plate sample in the simulation of another thickness sample. This work is centered on the use of LS-DYNA® material model *MAT_224, which uses a linear elastic curve, a series of hardening curves depending on rate and temperature, and a failure strain surface, depending on triaxiality and Lode parameter. The differences in tension yield stress and failure strain are used to adjust the baseline material model of a 0.5″ titanium alloy plate. The baseline material model is adjusted so that it matches the tensile test data of three other plate samples, with three different thicknesses.

Simple scaling of the yield stress and failure surface did not produce analytical predictions for the three other plates that matched the corresponding ballistic test results from the three other plates. This helps reinforce the knowledge that both yield and failure prediction are difficult problems and that processing of material for flight-critical hardware needs to be controlled as much as possible to limit the variability of material properties from batch to batch. Also, a significant match of the analysis and test can only occur when the parameters of the analytical material model are a close match to the properties of the test specimen material properties.

This first report identifies the challenge of obtaining an exact match to multiple, slightly different plates, both in mechanical properties and ballistic impact test predictions. This effort started with a predictive match to the original 0.5″ plate ballistic tests. That material model is applied to other plates with slightly different within-specification properties. The results raise the question of how to validate a model and what should be expected when using standard design values in conjunction with material models that are populated with test data from a single nominal plate. Follow-on work is underway, which will be reported in part 2 of this report.

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LCF	Failure surface dependency table
LCG	Failure strain rate dependency table
LCK1	Strain rate dependency table
LCKT	Temperature dependency table

EXECUTIVE SUMMARY

Predictive material modeling is demonstrated by having analytical predictions of the same condition match the observed test results. To match a test, the analytical model needs to match the actual plate material property, not the Metallic Material Properties Development and Standardization design or similar specifications. Titanium alloy (Ti-6Al-4V) with the same American Society for Metals specification, but with different processing and plate thickness, has varying mechanical properties. Any plates that are not from the same batch—including those from different suppliers, and different processing and thickness—have within-specification differences. Ideally, each plate thickness with different material properties needs to be treated as a new material, which requires a complete set of material tests to develop the constitutive model. Practically, such tests are expensive and time consuming. It is necessary to find a simple method to use the material model based on one plate sample in the simulation of another thickness sample. This work is centered on the use of LS-DYNA® material model *MAT_224, which uses a linear elastic curve, a series of hardening curves depending on the rate and temperature and a failure strain surface depending on triaxiality and Lode parameter. The differences in tension yield stress and failure strain are used to adjust the baseline material model of a 0.5″ Titanium alloy plate. The baseline material model is adjusted so that it matches the tensile test data of three other plate samples, with three different thicknesses.

Simple scaling of the yield stress and failure surface did not produce analytical predictions for the other three plates that matched the corresponding ballistic test results from the three other plates. This helps reinforce the knowledge that both yield and failure prediction is a difficult problem and that processing of material for flight critical hardware needs to be controlled as much as possible to limit the variability of material properties from batch to batch. Also, a significant match of the analysis and test can only occur when the parameters of the analytical material model are a close match to the properties of the test specimen material properties.

In this basic scaling study, the shape of the failure surface was not changed. The complete failure surface was raised and lowered in line with the tension test data. The base failure surface accurately reflects the failure strains for elements that erode in the 0.5″ plate ballistic tests and provide for a good match to those test exit velocities. However, in the ballistic impact tests, the elements that should erode and the states of stress of those elements differ from plate to plate. It is possible that in the other states of stress there are discrepancies between the details of the failure surface and more accurate and generic failure strains. It is also possible that the state of stress-dependent failure strains vary significantly from plate to plate and that a generic representative failure surface does not exist.

Another possibility is that the Von-Mises yield surface assumption of compression-tension symmetry, or perhaps isotropic behavior, made in *MAT_224 is not sufficiently valid for one or more of the three other thickness plates for accurate predictions to be made. An enhancement of *MAT_224 has been made, which allows the modeling of different compression and tension yield strengths and produces a generalized yield surface (*MAT_224_GYS). A new material model, which enables the modeling of anisotropic plastic behavior (*MAT_264), has also been added to LS-DYNA. *MAT_224_GYS and *MAT_264 offer opportunities for matching yield asymmetry and anisotropic plasticity observed in the Ti-64 plates to varying degrees, and may be investigated in future work.

This first report identifies the challenge of obtaining an exact match to multiple, slightly different plates, both in mechanical properties and ballistic impact test predictions. This effort started with a predictive match to the original 0.5″ plate ballistic tests. That material model is applied to other plates with slightly different within-specification properties. The results raise the question of how to validate a model and also what should be expected when using standard design values in conjunction with material models that are populated with test data from a single nominal plate. Follow-on work is underway, which will be reported in part two of this report.

1. INTRODUCTION

Titanium alloy Ti-6Al-4V is widely used in various industrial applications because of its advantageous mechanical and chemical properties. To aid the design and validation process, an advanced constitutive model *MAT_224 MAT_Tabulated_Johnson_Cook was created in the finite element solver LS-DYNA®. This fully tabulated constitutive material model enables one to define yield strength and failure strain as a function of 3D state of the stress, strain rate, and temperature. Using *MAT_224 in LS-DYNA, a material model of 0.5″ thickness Ti-6Al-4V plate (AMS-4911) was developed by matching 55 sets of material tests with different strain rates, temperatures, and state of stresses. This material model successfully predicts the low-to-medium speed ballistic impact test and all 55 mechanical property tests [1–2]

The mechanical properties of Ti-6Al-4V plate and sheet, with the same American Society for Metals specification, vary with batch, processing, and thickness [3]. This variation can be caused by the differences in chemical composition and microstructure resulting from the forming process that occur with different batches of Ti-6Al-4V. It is worthwhile to emphasize that the plate thickness is only one of the many factors that influence the mechanical properties of Ti-6Al-4V batches. The variation in mechanical properties can have a significant influence on the failure of material. Variations in material failure, in turn, can be critical in the design of crucial components. Accurate analytical test predictions are a basis for validation, and so accurate predictions are also critical.

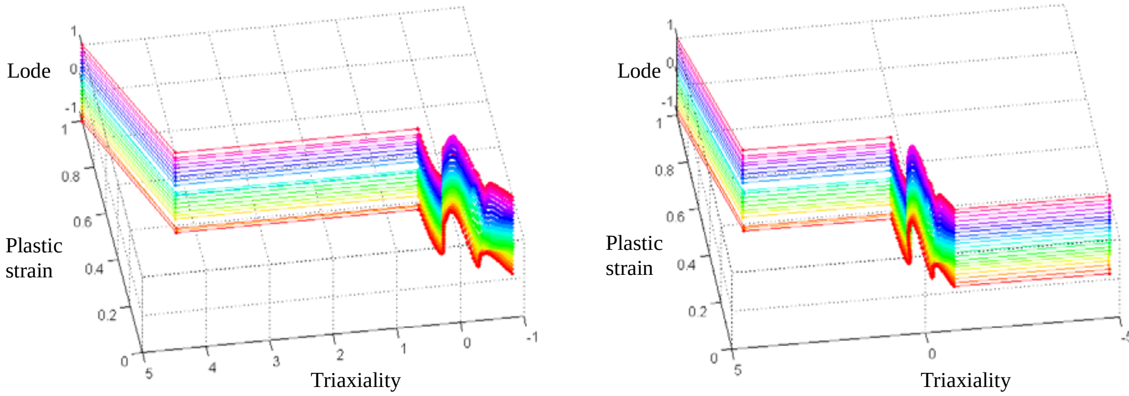
The plates used in this study are mill-run commercial grade, and specific processing was not defined. All plates met the specification, and so all individual plate properties are above minimum. There were four plates with four different thicknesses (i.e., 0.5″, 0.25″, 0.14″, and 0.09″) considered [2]. This report will evaluate the capability of a Ti-6Al-4V *MAT_224 material model created from 0.5″ plate test data for predicting impact tests on the 0.25″, 0.14″, and 0.09″ plates. The differences in tension yield stress and failure strain that were seen in the plates are used to adjust the baseline material model of the 0.5″ Ti-6Al-4V plate. Separate new materials models are created from the baseline material model so that each matched the tensile test data of each of the three other corresponding plate thicknesses. Using this scaling approach, an attempt is made to shift the material input parameters from the documented 0.5″ plate to the actual values of the other plates. Ballistic impact test predictions are made using the modified material models and are compared with the actual test results.

In this study, the shape of the failure surface was not changed. As discussed above, the complete failure surface was scaled so that the failure strain matched the tension test failure strain. Here, no attempt was made to make further adjustments to the failure surface to match either additional mechanical property tests or the ballistic impact test data.

2. THE 0.5″ TI-6AL-4V MATERIAL MODEL FAILURE SURFACE CORRECTION

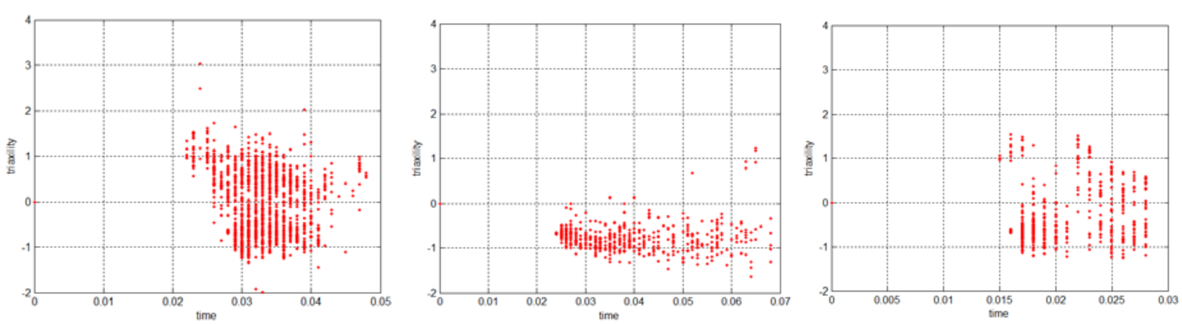
Failure strain varies as a function of the state of stress and is defined in *MAT_224 by a table input. Each curve of the table represents the failure strain versus triaxiality relation at a specific Lode parameter. The failure criterion can be seen as a surface defined in the 3-D space formed by triaxiality, Lode parameter and failure strain. Triaxiality and the Lode parameter are a means of measuring and tracking the 3D state of stress. The failure surface was created by matching the failure condition of many tests that had differing states of stresses.

In LS-DYNA, when abscissa values beyond those defined on a curve are referenced the last two data points are extrapolated to provide the ordinate value. Therefore, LS-DYNA will also extrapolate the failure surface based on the last two data points the user defined. In the original 0.5″ material model, a plateau was added to maintain a constant failure strain for triaxiality between 0.66 and 4.0 (see figure 1) to prevent the arbitrary extrapolation to physically unrealistic strain values. Notice that most of the failed elements (see figure 2) of the 0.5″ impact test simulation map to a triaxiality between -1 and 2, which is well defined in the original Ti-6Al-4V *MAT_224 model (see figure 1).



(a) (b)

Figure 1. Failure surface of (a) original *MAT_224 model and (b) modified *MAT_224 model with the plateau fix



(a) (b) (c)

Figure 2. Triaxiality of the failed elements in Ti-6Al-4V plate impact test simulation for (a) 0.5″, (b) 0.14″, and (c) 0.25″

A problem was discovered when the original 0.5″ Ti-6Al-4V *MAT_224 material model was used to simulate the impact test of 0.14″ plate, which had a different failure mode and thus failed under a different state of stress. A large number of failed elements map to the region with triaxiality below -1. The failure surface is quite steep near triaxiality of -1, which means that the original 0.5″ Ti-6Al-4V *MAT_224 material model will extrapolate sharply downward and will give an unrealistically small failure strain for triaxiality of less than -1. It was necessary to revise the original 0.5″ material model by adding a plateau to the very negative triaxiality region for the same reason the plateau was added to the positive side.

Backward compatibility check runs show that the revised 0.5″ Ti-6Al-4V *MAT_224 material model performs equally as well as the original simulations of the 0.5″ impact test [4]. Results show that the revised 0.5″ Ti-6Al-4V *MAT_224 model with plateau fix has almost identical exit velocities (see figure 3) and plugging shape (see figure 4) as the original 0.5″ Ti-6Al-4V *MAT_224 material model. Therefore, all simulations in this work use the revised 0.5″ Ti-6Al-4V *MAT_224 model with the plateau fix and is the baseline material model.

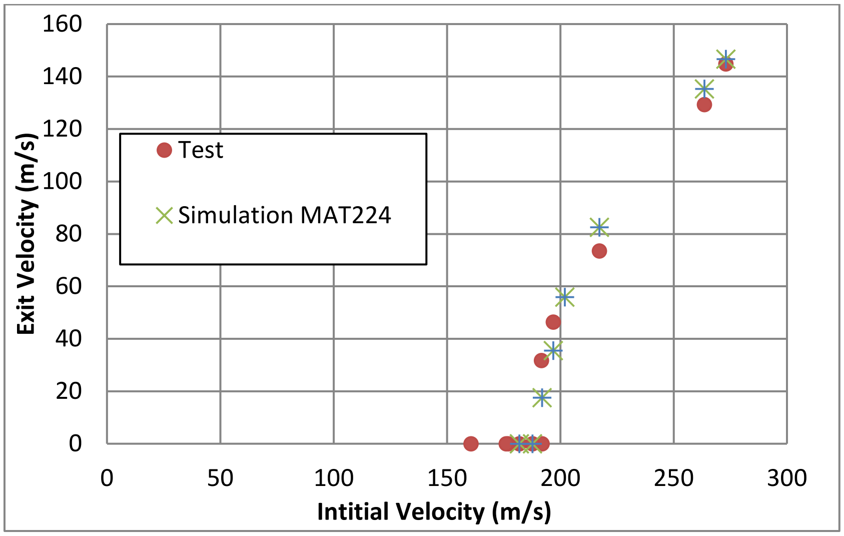


Figure 3. Impact test [4] and simulation comparison for 0.5″ Ti-6Al-4V plate for original the *MAT_224 model and the modified *MAT224 model with the plateau fix

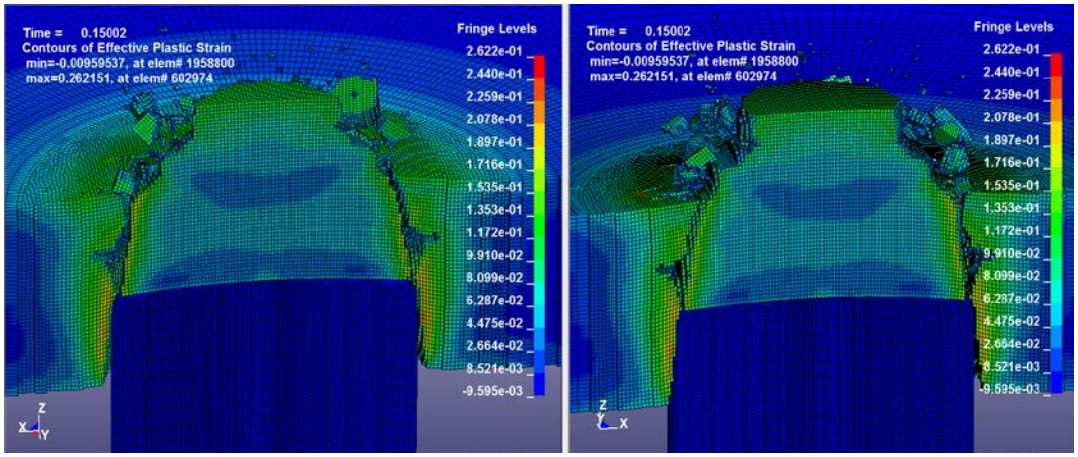


Figure 4. 0.5″ Plate impact simulation comparison of the original 0.5″ Ti-6Al-4V *MAT_224 model and the modified 0.5″ Ti-6Al-4V *MAT_224 model with the plateau fix

3. SCALING METHODOLOGY

Two scaling approaches are introduced to quickly address variations of the mechanical properties among plates of different thickness with the same material specification. The first approach is to scale the yield surface uniformly. The second approach is to also scale the failure surface, in additional to the scaling of the yield surface. The scaling is based on comparing the stress-strain curves from the tensile tests of the different thicknesses Ti-6-Al-4V plates. Other scaling approaches were considered but not pursued because of the resulting mechanical properties being judged to likely be non-physical.

The tensile tests at the strain rate of approximately 1/s are used for scaling. Low-strain rate tension tests are the most common mechanical property test, which produce the most widely available test data. This low-rate tensile test offers a general idea of how the materials behave differently because of minor within-specification deviations in actual batches of material. The 1/s test data is available for all four plate thicknesses of 0.5″, 0.25″, 0.14″, and 0.09″ used in this study. The scaling for the 0.25″ plate material model is demonstrated in detail, and the scaling for the other thickness plates follow the exact same procedure. Figure 5 shows a comparison of the 0.5″ plate and the 0.25″ plate tensile tests at a strain rate of 1/s.

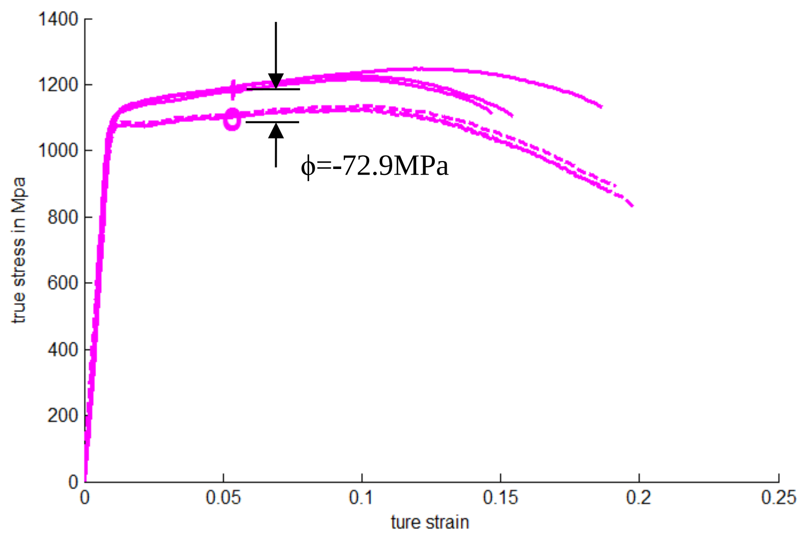


Figure 5. Tensile stress-strain comparison between the 0.5″ Ti-6-Al-4V plate (solid line) and the 0.25″ Ti-6Al-4V plate (dash line) [3]. Strain rate = 1/s

True stress, σ, and true strain, ε, are calculated by:

$$\varepsilon = \ln(1+\varepsilon_{eng})$$
$$\sigma = \sigma_{eng}(1+\varepsilon) \qquad (1)$$

where engineering strain is $\varepsilon_{eng} = l / l_o$, l_o and l are the initial and current length of the extensometer, respectively, engineering stress is $\sigma_{eng} = F / A_o$, F is the applied force, and A_o is the undeformed cross-section area. The true strain ε (see eq.1) is equivalent to the one-dimensional

Hencky strain [5] and to the logarithmic strain [6]. The true stress σ (see eq. 1) is the one-dimensional Kirchhoff stress [5]. The true stress and true strain calculated with this simple formula is not valid beyond necking point. Before necking, the only non-zero component of stress and strain tensors are ε_{11} and σ_{11}, therefore the one-dimensional equation (see equation 1) is valid. After necking, all components of the stress and strain tensor have non-zero values, and the one dimensional equation does not hold [1].

When developing a new *MAT_224 input deck, iterative reverse engineering is used to create an accurate stress-strain curve beyond the necking point. The goal of this effort is to evaluate a simple correction to account for differences in yield stress between plates, so the full reverse-engineering step is omitted. The adjusted true stress-true strain curve is directly calculated from the simple definition of equation 1. The differences in yield stress, which are used to calculate the scaling factor for yield stress, are compared prior to necking (see figure 5). Although the absolute value of failure strain is not accurate past the necking point, the relative differences of failure strain can be used to scale the failure surface.

Differences in temperature dependency are also evaluated. Despite differences in room temperature stress-strain curves, differences are minimal at elevated temperatures. Figure 6 shows the stress-strain curves at varying temperatures for the 0.5″ and 0.25″ thickness plates [3]. This is consistent with the microstructure causing room temperature differences and the elevated temperatures causing partial annealing. This partial annealing then reduces the influence of the microstructure on the mechanical properties. Therefore, the original evaluated temperature stress-strain curves, from the baseline 0.5″ material model, are retained for all of the other scaled thickness models.

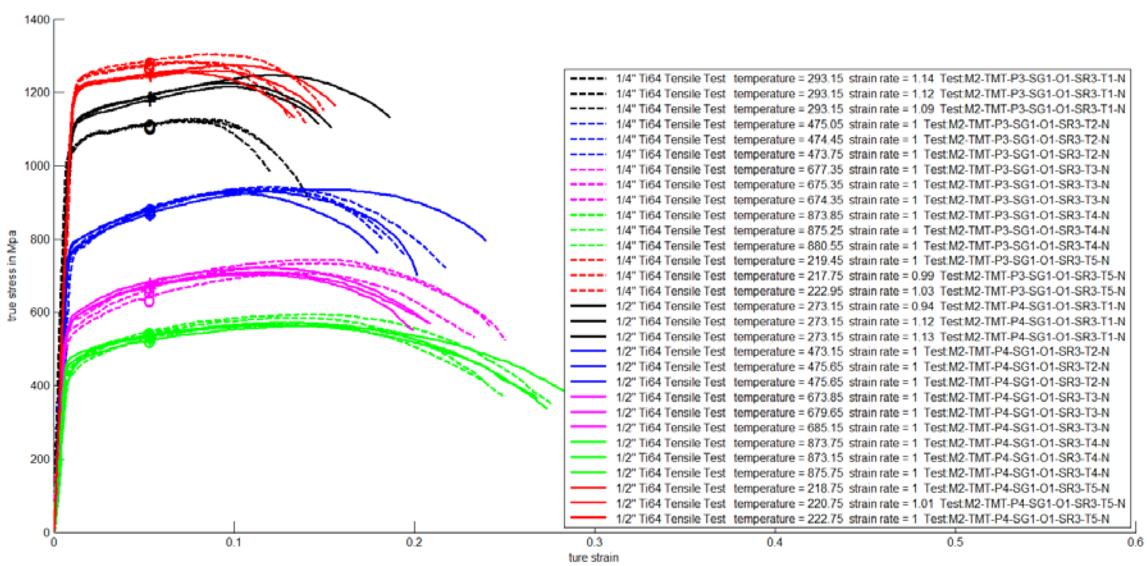


Figure 6. Stress-strain relation under different temperatures for the 0.5″ and the 0.25″ plate [3]

3.1 YIELD SURFACE SCALING

Testing at 1/s generally produces some scatter and variability as the data transitions from linear elastic behavior to plastic deformation. To avoid the part of the stress-strain curve with high variability, the average value of stress at 5% strain is picked for computing the offset factor for the plastic stress-strain curves defining the yield surface. The offset factor ϕ is defined as:

$$\phi \equiv \sigma_{0.25} - \sigma_{0.5} \tag{2}$$

where $\sigma_{0.5}$ and $\sigma_{0.25}$ are the average of stress value at 5% strain for the 0.5″ and 0.25″ thickness plates, respectively.

The original plastic stresses of the 0.5″ plate can be expressed as:

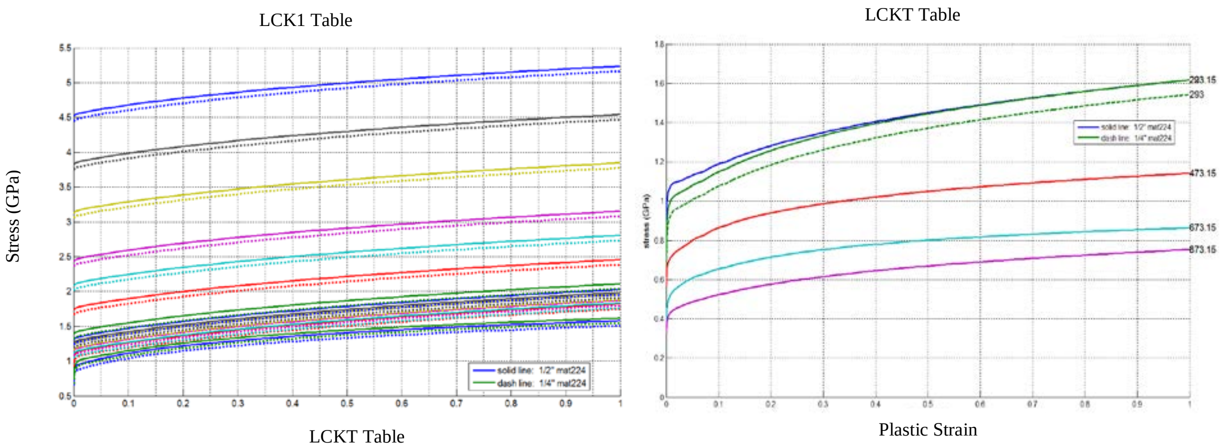
$$\boldsymbol{\sigma} = y^{0.5"}(\boldsymbol{\varepsilon}, \dot{\boldsymbol{\varepsilon}}, T...) \tag{3}$$

Next, the offset factor ϕ is used to create the new set of stress-strain curves. The plastic stresses of the 0.25″ plate offset material model can be expressed as:

$$\boldsymbol{\sigma} = y^{0.25"}(\boldsymbol{\varepsilon}, \dot{\boldsymbol{\varepsilon}}, T...) = y^{0.5"}(\boldsymbol{\varepsilon}, \dot{\boldsymbol{\varepsilon}}, T...) + \phi \tag{4}$$

where $\boldsymbol{\sigma}$ is the stress tensor, $\boldsymbol{\varepsilon}$ is the strain tensor, and $\dot{\boldsymbol{\varepsilon}}$ is the strain rate tensor. The terms $y^{0.5"}$ and $y^{0.25"}$ denote the yield surface of 0.5″ and 0.25″ plate, respectively. In terms of LS-DYNA keyword input, equation 4 will create an offset to all the stress-strain curves that define yield surface (e.g., strain rate dependency table (LCK1) in *MAT_224) by ϕ to create the adjusted material model (see figure 7(a)).

As required by *MAT_224, the quasi-static curve of the LCK1 and the room temperature curve of the temperature dependency table (LCKT) must be identical [1, 7–9]. Therefore, the room temperature curve of LCKT table is changed accordingly to match the adjusted quasi-static curve (see figure 7(b)).



(a) (b)

Figure 7. (a) strain rate dependency LCK1 table for the 0.5″ and 0.25″ plates and (b) temperature dependency LCKT table for the 0.5″ and 0.25″ plates

The first scaling approach only offsets the LCK1 table of 0.5″ Ti-6Al-4V *MAT_224 by the difference in stress at 5% strain of the tensile test for the two thicknesses. The 1/s temperature stress-strain curve in the LCKT is also modified with the exact curve created in LCK1 at 1/s. Therefore, this first approach will only attempt to compensate for the differences in yield stresses.

3.2 FAILURE SURFACE SCALING

The second approach will attempt to compensate for the differences in failure strains and the differences in yield stress. Therefore, the failure surface will be modified and the the stress-strain curves in the first approach will be offset.

There is significant scatter in the failure strains of both the 0.25″ and 0.5″ thickness plates (see figure 8). The average failure strains, at the benchmark strain rate of ~1.0 (1/s), will be used as a basis to compare the failure strains. The difference between the 0.25″ and 0.5″ thickness plates is:

$$\Delta\varepsilon^{1/\mathrm{sec}} = \varepsilon_{0.25''} - \varepsilon_{0.5''} = -0.0349 \tag{5}$$

where $\Delta\varepsilon^{1/\mathrm{sec}}$ is the difference in failure strain defined at strain rate ~1.0 (1/s), and $\varepsilon_{0.25''}$ and $\varepsilon_{0.5''}$ are the average tensile failure strains of the 0.25″ and 0.5″ plates, as calculated using equation 1. Again, $\varepsilon_{0.25''}$ and $\varepsilon_{0.5''}$ are not actual plastic failure strain because the true strain after necking was not calculated. These two values only offer a relative comparison that is then used as the scaling factor.

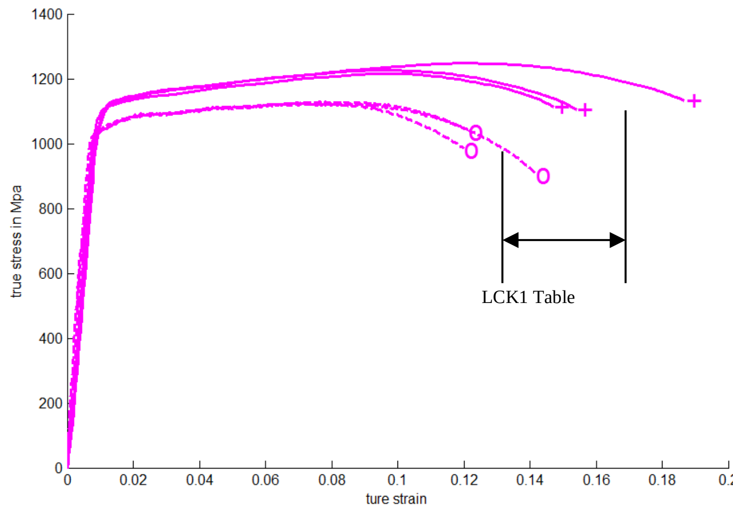


Figure 8. Stress-stress relation and failure strains of the 0.5″ (solid line) and 0.25″(dash line) plates[3]

There is a strain rate dependency in the failure strain of Ti-6Al-4V. In the original 0.5″ thickness material model [1] the baseline strain rate in the failure strain rate dependency table (LCG) is defined at a rate of 0.01 (1/s) (see figure 9). This baseline strain rate definition is retained in the scaled models. The failure strain at a strain rate of 1.0 (1/s) was calculated to be 90% that of a strain rate of 0.01 (1/s) [1].Therefore, a scaling factor 0.9/1.0 has to be applied to convert the failure strain at 1.0 (1/s) to that of 0.01 (1/s).

$$\Delta\varepsilon^{0.01/\text{sec}} = 10/9\Delta\varepsilon^{1/\text{sec}} = -0.0388 \tag{6}$$

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$                Failure - Strain Rate Curve                          $
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_CURVE
$      LCID      SIDR       SFA       SFO      OFFA      OFFO     DATYP
       4000
$                  A1                  O1
             0.000010               1.000
             0.001000               0.900
             2.350000               0.370
             6.610000               0.370
```

Figure 9. Strain rate dependency table of failure strain. The unit of time and strain rate is (1/1000 sec). The scaling factor has no units

Next the actual tensile failure strain $e_{0.5''}$ in the baseline 0.5″ *MAT_224 material model[1] was defined. The simple tensile test fails at a triaxiality = -0.39 and at a Lode parameter = 1. Therefore, the reference failure strain of the 0.5″ plate $e_{0.5''}$ can be readily looked up in the failure surface dependency table (LCF) that defines the state of stress dependency of the failure [1]. Now the scaling factor is:

$$\mu \equiv \left(e_{0.5''} + \Delta\varepsilon^{0.01/\text{sec}}\right)/e_{0.5''} = 0.9750 \tag{7}$$

The last step is to apply the scaling factor to all curves in the state of stress LCF:

$$e_{0.25''} = \mu e_{0.5''} \tag{8}$$

The reason for this operation is to guarantee that the difference of failure strain calculated using equation 1 equals the difference of the failure strain, at the tensile state of stress, between the baseline and the scaled *MAT_224 material models. The final product is a failure surface slightly lower than the baseline failure surface as shown in figure 10.

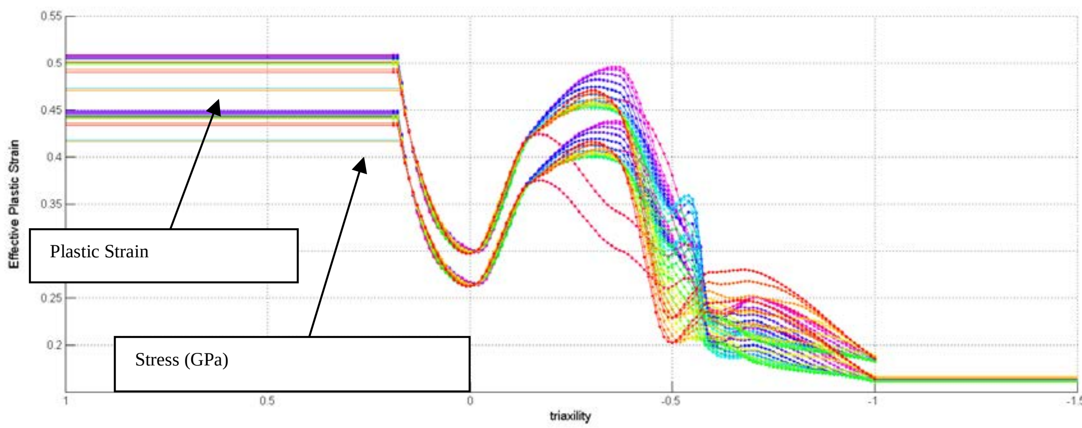


Figure 10. Baseline 0.5″ and scaled 0.25″ failure surface at a glance

The second scaling approach includes the LCK1 offset that compensates for the differences in yield stress, and scaling the failure surface of 0.5″ Ti-6Al-4V *MAT_224 to compensate for the differences in failure strain. The scale factor ensures that the difference between failure strain tables at the tension state of stress for the baseline and modified material models equals the failure strain difference calculated with the simple formula (see equation 1).

4. SIMULATION RESULTS

*MAT_224 material models for the 0.25″, 0.14″, and 0.09″ thickness plates were created by scaling the baseline 0.5″ plate *MAT_224 material model, following the procedure described in section 3. The baseline material model was created from the original 0.5″ Ti-6Al-4V material model by including the plateau fix (see section 2). The offset factors for the material models of the different thickness plates are summarized in table 1, with the tension stress-strain curves also being shown in figure 11.

Table 1. Yield (LCK1) offset factors for different plate thickness Ti-6Al-4V *MAT_224 material models

Material Model	Offset Factor ϕ (MPa)
0.5″ *MAT_224	0
0.25″ *MAT_224	-72.9
0.14″ *MAT_224	-80.5
0.09″ *MAT_224	-71.2

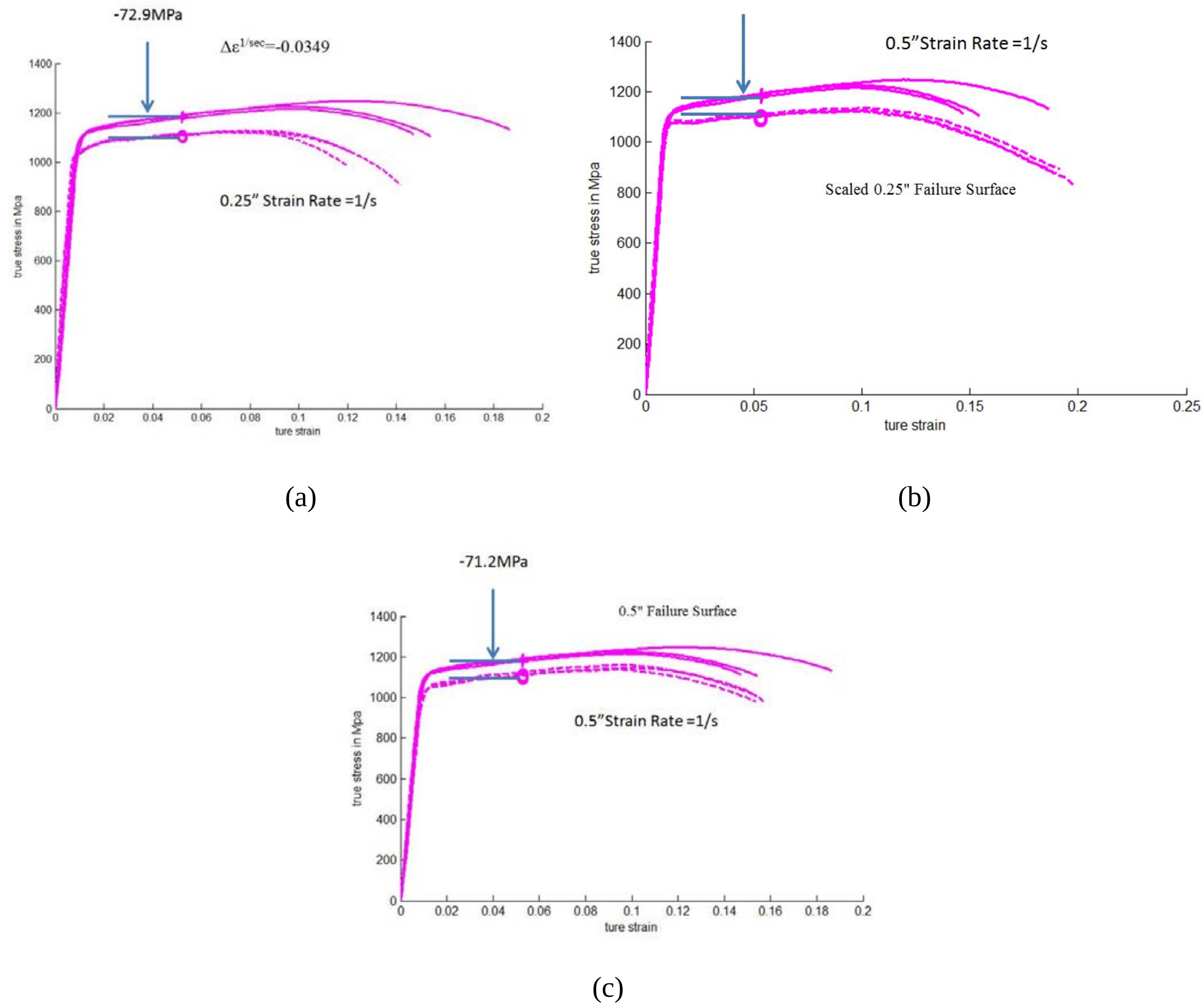
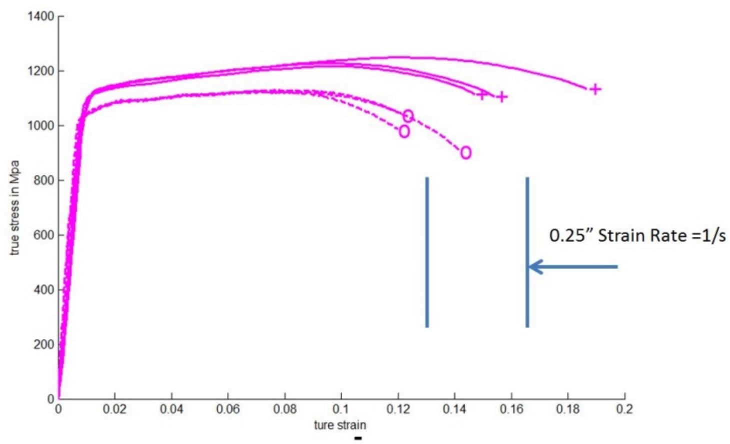


Figure 11. (a) Ti-6Al-4V yield offset of 0.25″(dash line) and 0.5″ (solid line) plate, (b) Ti-6-Al-4V yield offset of 0.14″(dash line) and 0.5″ (solid line) plate, and (c) Ti-6-Al-4V yield offset of 0.09″(dash line) and 0.5″ (solid line) plate [3]

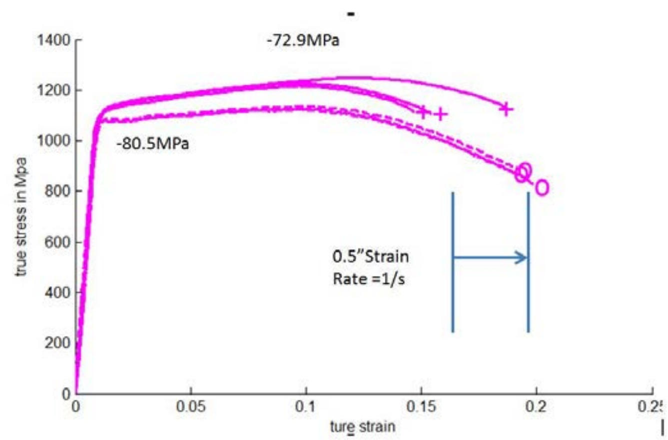
The scaling factor and the amount of failure strain adjustment are summarized in table 2, with the tension stress-strain curves also being shown in figure 12.

Table 2. LCF scaling factors for different thickness plate Ti-6Al-4V *MAT_224 material models

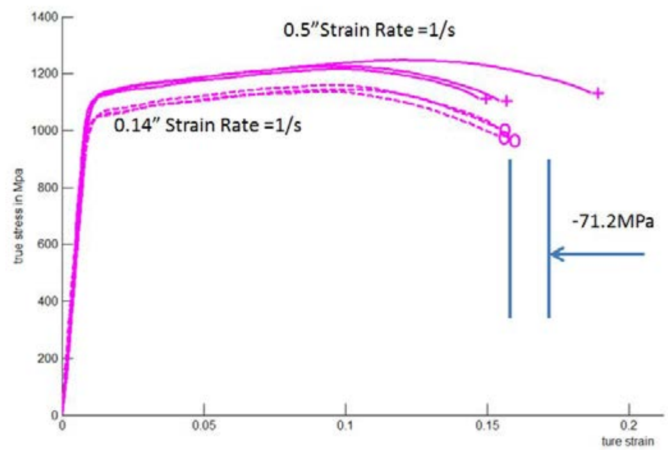
Material Model	Scale Factor μ
0.5″ *MAT_224	1
0.25″ *MAT_224	0.8840
0.14″ *MAT_224	1.1022
0.09″ *MAT_224	0.9750



(a)



(b)



(c)

Figure 12. (a) Ti-6-Al-4V failure offset of 0.25″(dash line) and 0.5″ (solid line) plate, (b) Ti-6-Al-4V failure offset of 0.14″(dash line) and 0.5″ (solid line) plate, and (c) Ti-6-Al-4V failure offset of 0.09″(dash line) and 0.5″ (solid line) plate [3]

For each plate thickness, three material model variations are used to simulate the ballistic impact tests, and the analytical exit velocities are compared with the impact test exit velocities [4]. The three material model variations are: 1) the baseline 0.5″ plate material model with the plateau fix; 2) the material model with only the LCK1 offset; and 3) the material model with both LCK1 offset and LCF scaling.

For the 0.25″ thickness plate, the ballistic limit prediction using the baseline 0.5″ model was ~19% higher than the ballistic test (see figure 13). Adjusting the LCK1 to match the 0.25″ tension test had no effect on the predicted exit velocities. Adding in the adjustment to the LCF caused the exceedance to be reduced to ~14% higher than the test, which is only a slight improvement.

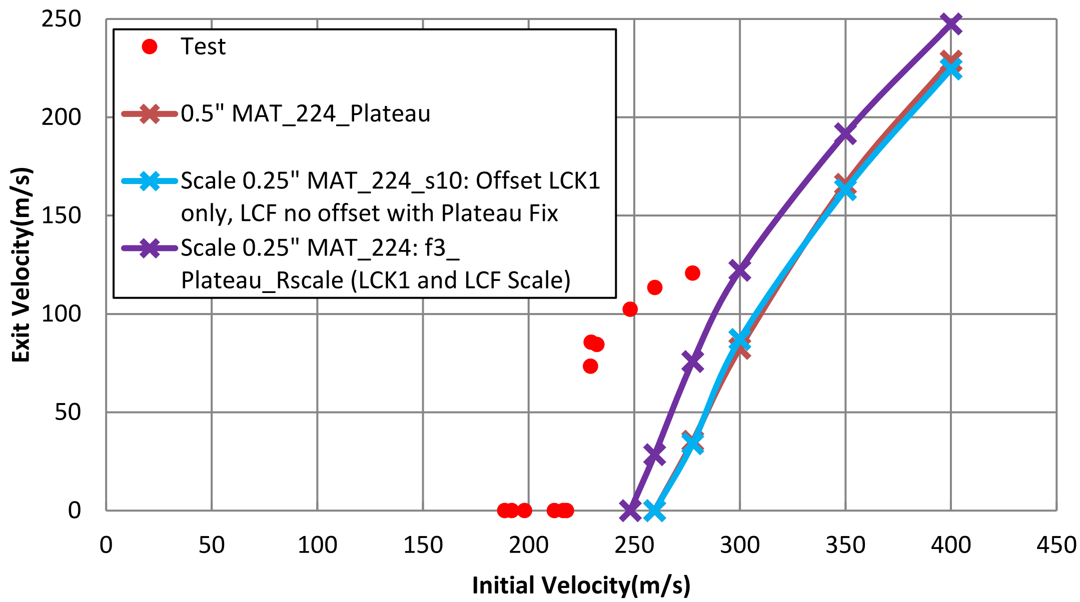


Figure 13. Initial velocity vs. exit velocity in the simulation of 0.25″ plate with three different material models

For the 0.14″ thickness plate, the ballistic limit prediction using the baseline 0.5″ model was ~10% higher than the ballistic test (see figure 14). In this case, adjusting the LCK1 to match the 0.14″ tension test created a good match to the test ballistic limit, although there is divergence from the test exit velocities at higher velocities. For this plate thickness, the adjustment to the LCF was an increase (see table 2 and figure 12), and counter-intuitively, this increase in the failure strain caused the predicted ballistic limit to be reduced to ~13% below the test ballistic limit. The reason for this counterintuitive result will be discussed in section 5.

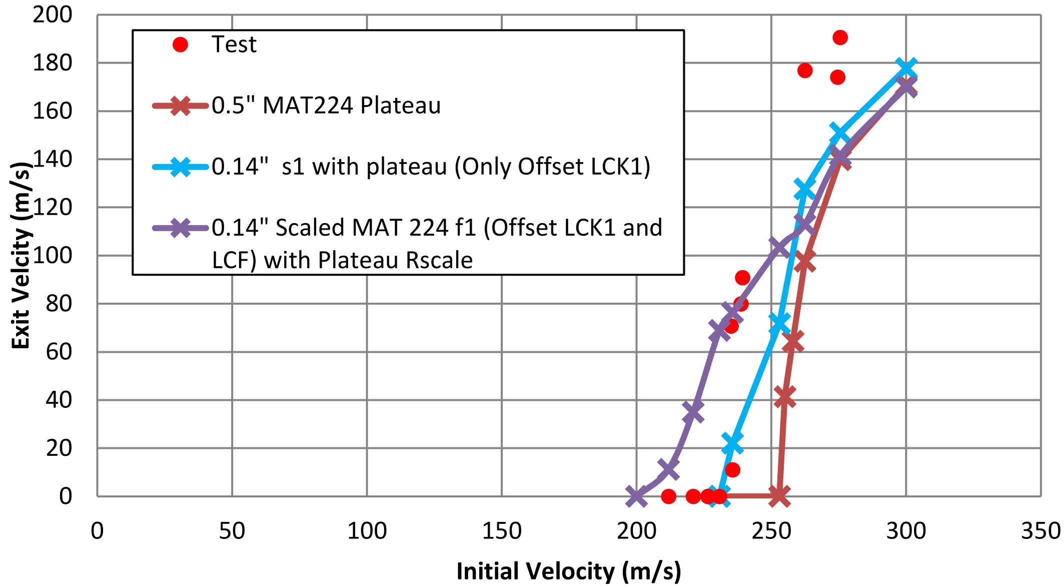


Figure 14. Initial velocity vs. exit velocity in the simulation of 0.14″ plate with three different material models

For the 0.09″ thickness plate, the ballistic limit prediction using the baseline 0.5″ model was ~23% below that of the ballistic test (see figure 15). Adjusting the LCK1 to match the 0.09″ tension test had no significant effect on the predicted exit velocities. Adding in the adjustment to the LCF had no significant effect on the predicted exit velocities.

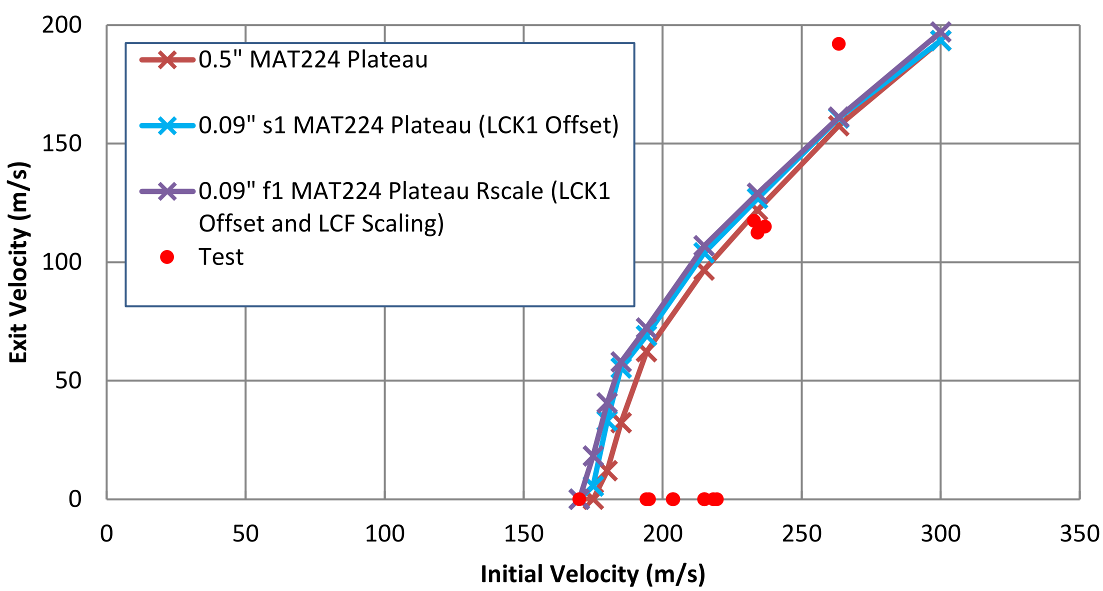
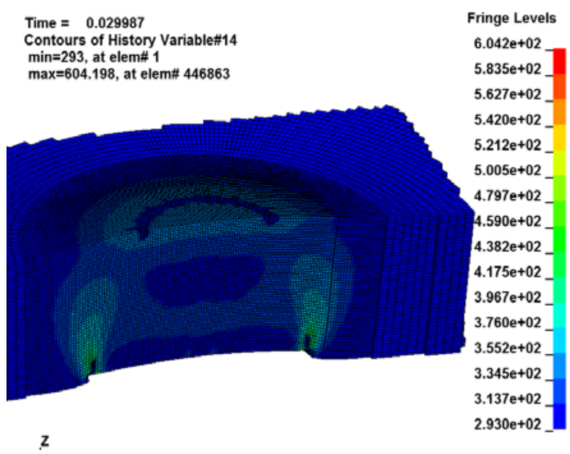


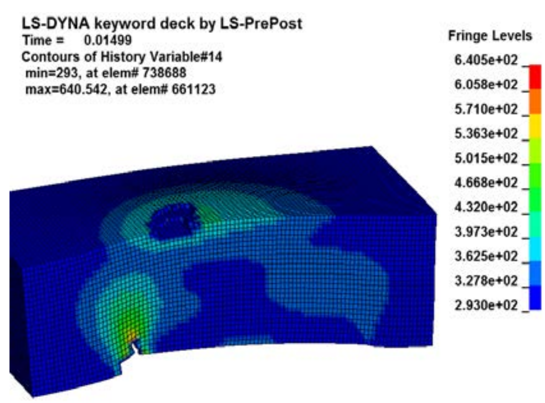
Figure 15. Initial velocity vs. exit velocity in the simulation of 0.09″ plate with three different material models

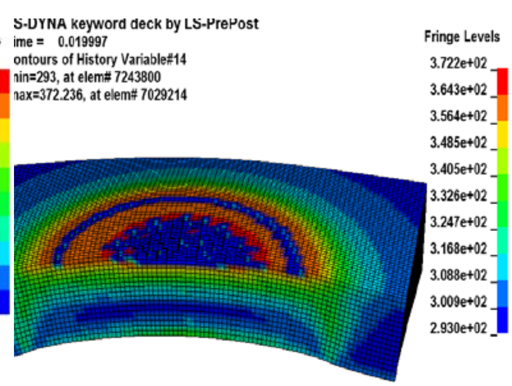
Only in the 0.14″ impact test predictions did the adjustment to the yield surface (LCK1 offset) have a significant effect on the exit velocities. For the predictions with both the LCK1 offset and LCF scaling modifications, the results vary from having a small positive effect on the 0.25″ plate predictions, a negligible effect on the 0.09″ plate predictions, and a negative counter-intuitive effect on the 0.14″ plate predictions. No clear pattern on the usefulness of scaling to match tension test results emerges. Some of the reasons why the scaling in this study was not effective are discussed in section 5.

It is noted that the temperature predictions can be vary greatly among the plates of different thicknesses. For instance, the temperature at the initial failure time is approximately 604 K for the 0.5″ plate and 640 K for the 0.25″ plate, compared with 372 K for the 0.14″ plate (see figure 16).



(a)





(b) (c)

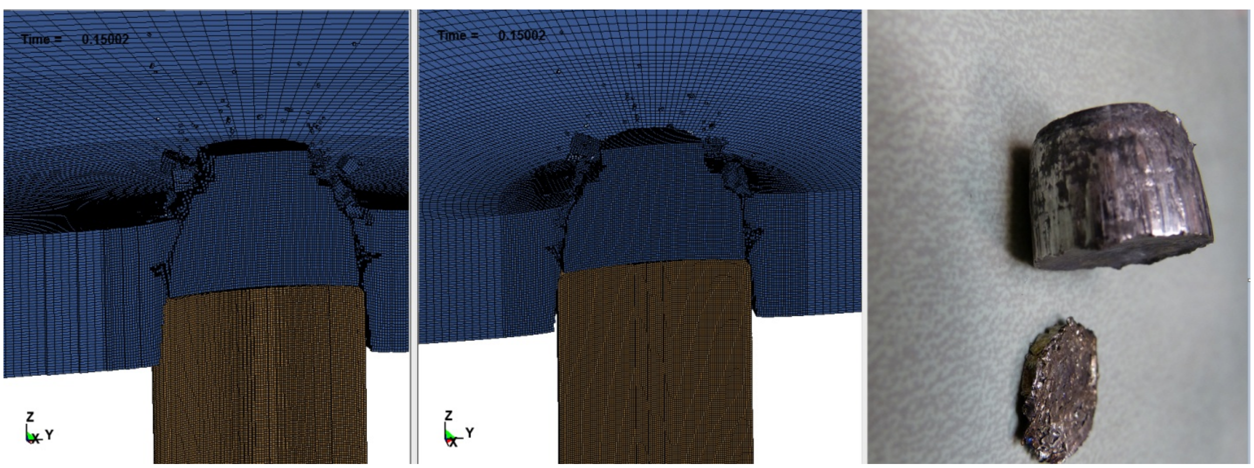
Figure 16. Temperature contour of (a) the 0.50″ impact test, (b) the 0.25″ impact test, and (c) the 0.14″ impact test simulated with the baseline 0.5″ *MAT_224 with plateau fix

5. DISCUSSION

No repeatable pattern of the scaling's influence on exit velocities was demonstrated. No repeatable pattern of improvement in exit velocity prediction was demonstrated using either scaling approach. Some of the reasons why scaling was not effective are discussed in separate discussions for each plate (see sections 5.2, 5.3, and 5.4). The reason why scaling was not effective is different for each of the plates.

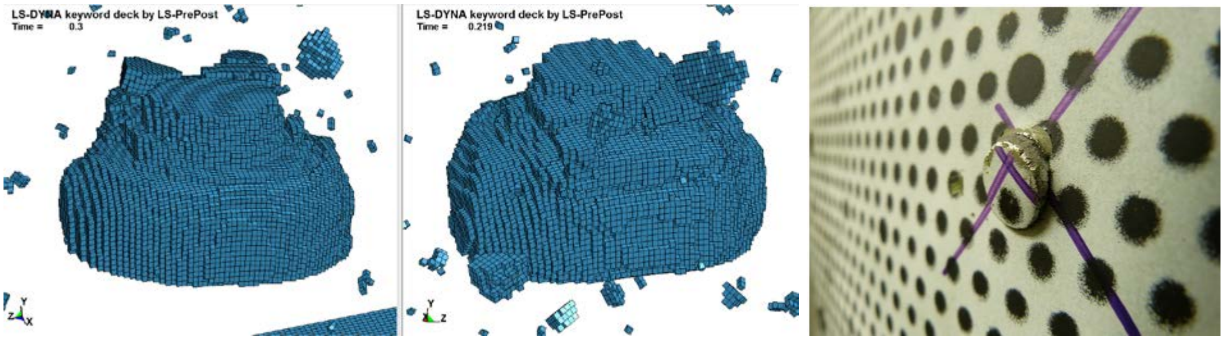
5.1 THE 0.5″ TI-6AL-4V MATERIAL MODEL FAILURE SURFACE CORRECTION

As noted in section 2, the correction of the 0.5″ *MAT_224 material model with the plateau fix had little effect on the predictions of the 0.5″ impact tests. For the 0.5″ plate simulation, the model with or without the correction predicts the plugging shape fairly well (see figure 17). However, when comparing the impact test predictions using the original 0.5″ model with the baseline plateau fix 0.5″ model, some slight improvement in the predicted plugging shape is observed for the other three thicknesses. There is a slight decrease in the number of elements, which are incorrectly removed (see figures 18–20). For these other thicknesses, in general, neither simulation represents the actual plug shape accurately.



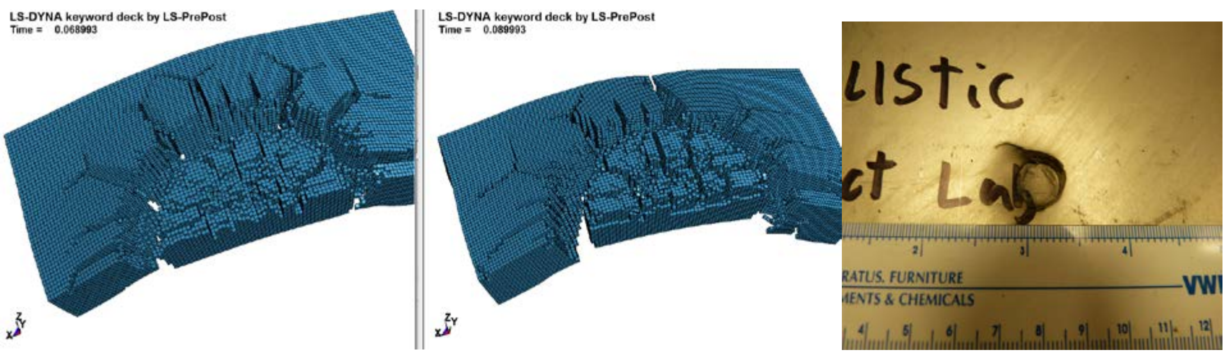
(a) (b) (c)

Figure 17. Plug shape of 0.5″ impact simulation with (a) the original 0.5″ *MAT_224 material model, (b) baseline 0.5″ *MAT_224 material model with the plateau fix, and (c) test ″DB178″



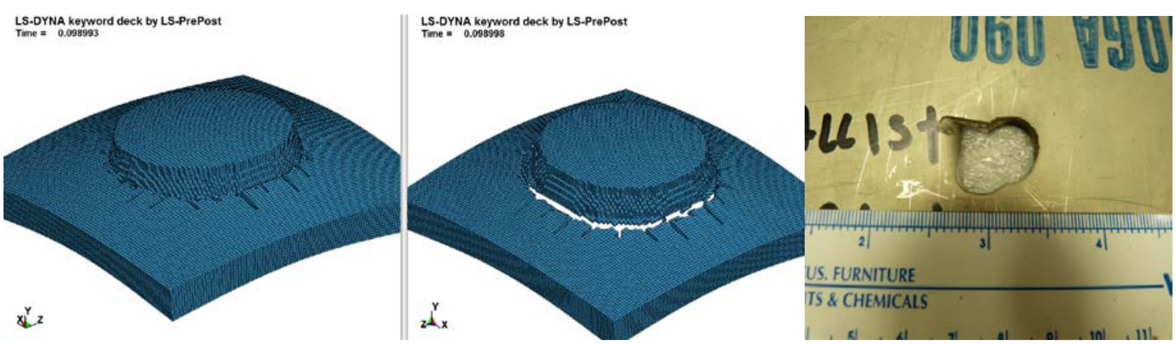
(a) (b) (c)

Figure 18. Plug shape of 0.25″ impact simulation with (a) the original 0.5″ *MAT_224 material model, (b) baseline 0.5″ *MAT_224 material model with the plateau fix, and (c) test



(a) (b) (c)

Figure 19. Plug shape of 0.14″ impact simulation with (a) the original 0.5″ *MAT_224 material model, (b) baseline *MAT_224 material model with the plateau fix, and (c) test

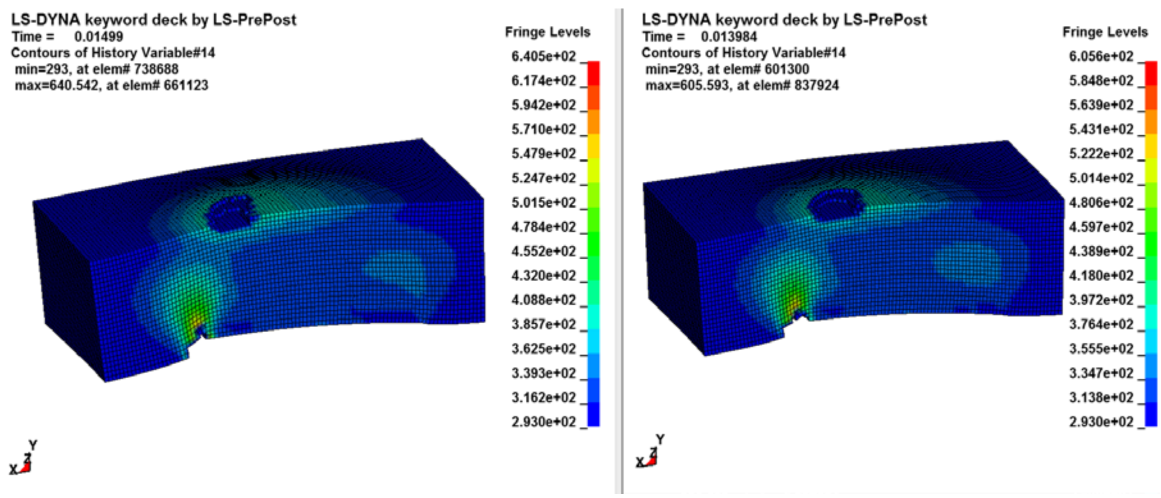


(a) (b) (c)

Figure 20. Plug shape of 0.09″ impact simulation with (a) original 0.5″ *MAT_224 material model, (b) baseline 0.5″ *MAT_224 material model with the plateau fix, and (c) test

5.2 THE 0.25″ THICKNESS PLATE

In simulations of impacts onto the 0.25″ thickness plate, the scaling of the yield surface had no effect and the scaling of the failure surface had only a small effect on the exit velocities (see figure 13). This is because the temperatures in the failure region rise to where they dominate the physics of the impact. The simulations with the baseline and the scaled material models show that the material in the region of failure predicts very high temperatures of more than 600 K (see figure 21). As discussed in section 3, the stress-strain curves are almost identical for 0.25″ and 0.5″ plates at these high temperatures (see figure 6). The differences in the mechanical properties at room temperature are due to the microstructure differences introduced during the manufacturing process. As temperatures go higher, partial or total annealing will occur, and differences in microstructure and mechanical properties will be reduced or eliminated. Therefore, because of the high temperatures, the scaling of the yield surface does little to change the predicted exit velocities of the 0.25″ thickness plate (see figure 13).

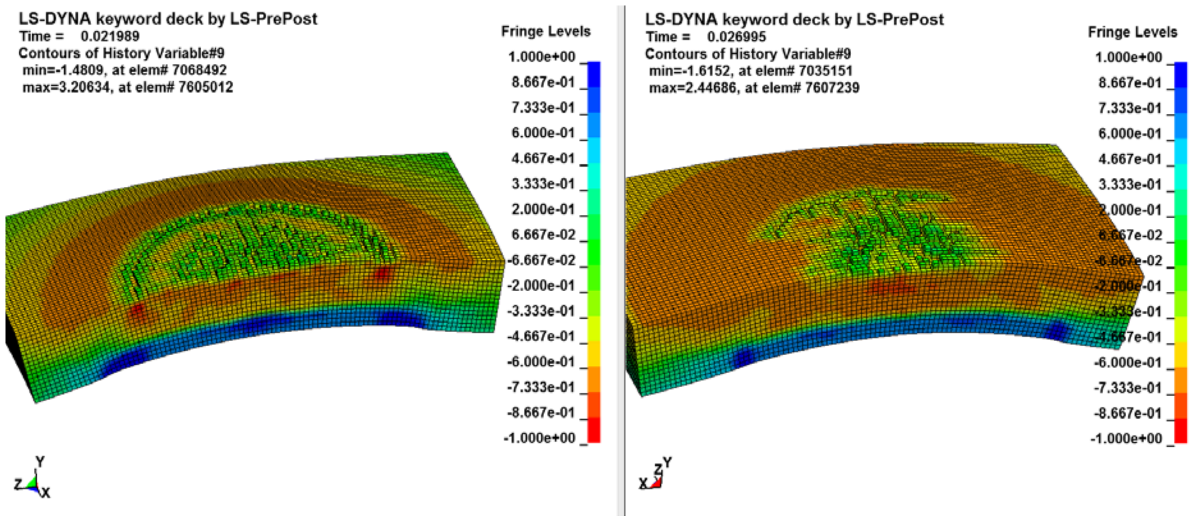


(a) (b)

Figure 21. Temperature contour of 0.25″ impact test, simulated with (a) 0.5″ *MAT_224 with plateau fix and (b) 0.25″ *MAT_224 yield and failure surface scaled model; both simulations are of the same initial speed

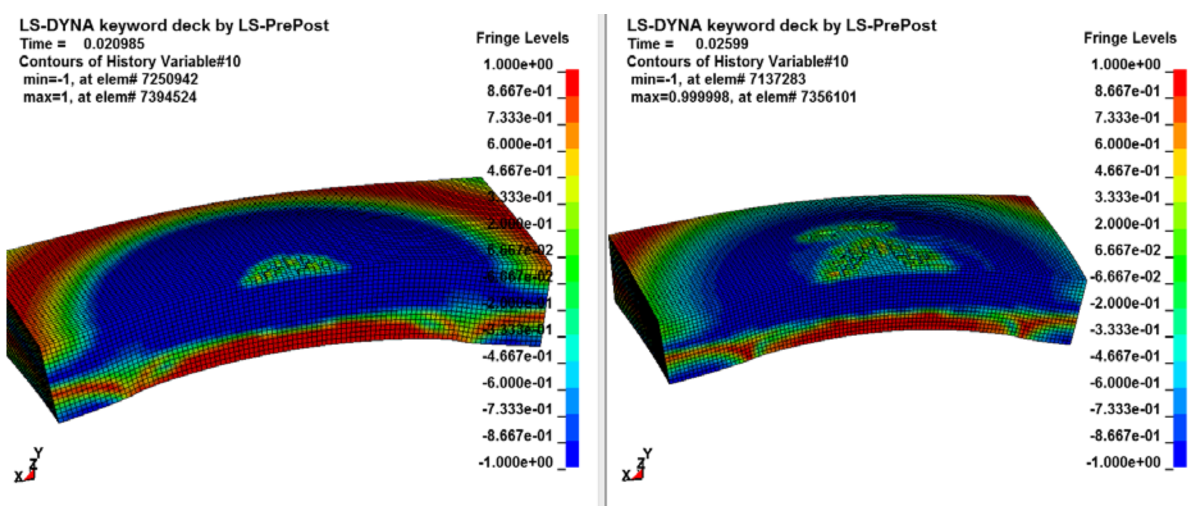
5.3 THE 0.14″ THICKNESS PLATE

In simulations of impacts onto the 0.14″ thickness plate, adjusting the yield surface created a good match to the test ballistic limit, but not a good match to the higher velocity impacts (see figure 14). The increase in the failure strain counter-intuitively reduced the predicted velocities to below the test exit velocities (see figure 12). In the 0.14″ thickness plate simulations, element erosion begins in the center of the plate, opposite the side of the impact (see figures 22–23). It is important to note that the backside erosion did not occur in the actual test (see figure 19). Different lode and triaxiality parameters are observed resulting from the scaled and baseline material model predictions (see figures 22–23). The failure surface was increased overall, but the specific failure point moved to a different location in the 3-D surface, as defined by triaxiality, lode, and plastic failure strain (see figure 10). This different state of stress has a lower failure strain in the state of stress predicted by the baseline model. Although the failure surface was increased overall, the specific failure strain at the location of failure was lower using the scaled model.



(a) (b)

Figure 22. Triaxiality comparison for 0.14″ plate simulated with (a) 0.5″ MAT_224 and (b) 0.14″ scaled MAT_224; both are the simulations with lowest exit velocity that are simulated



(a) (b)

Figure 23. Lode comparison for 0.14″ plate simulated with (a) 0.5″ MAT_224 and (b) 0.14″ scaled MAT_224; both are the simulations with lowest exit velocity that are simulated

5.4 THE 0.09″ THICKNESS PLATE

In simulations of impacts onto the 0.09″ plate, neither the scaling of the yield surface nor the scaling of the failure surface has much effect on the exit velocities (see figure 14). A limited parameter study demonstrated that the exit velocity is insensitive to the yield strength for this particular set of impact conditions, on this particular plate, with this particular material model (see figure 24). The 0.09″ thickness plate material model with only the yield surface offset was taken as the baseline. All yield curves were offset to 105% and 85% of the yield strength to study the sensitivity.

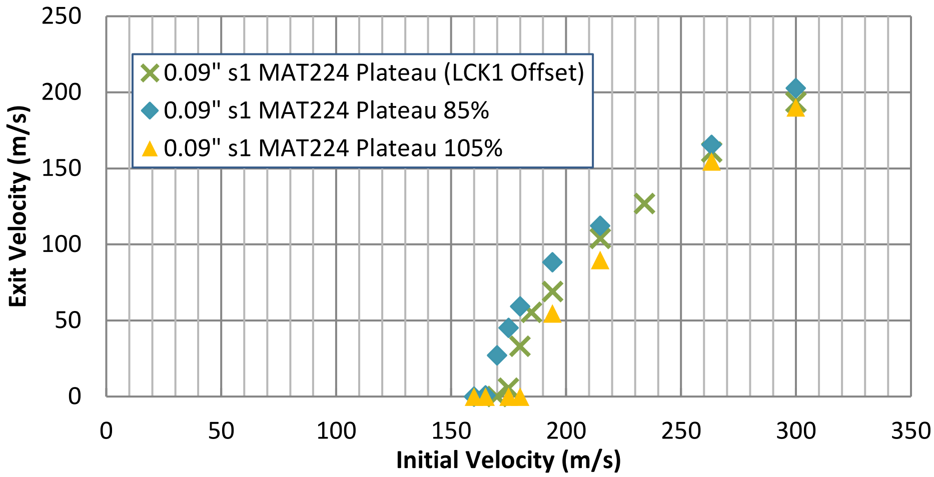


Figure 24. Parametric study for 0.09″ plate impact test

Neither the exit velocities (see figure 15) nor the failure mode (see figure 20) were predicted well using the baseline model. Neither scaling the yield surface nor the failure surface fundamentally improved the match between the analysis and test. As with the other two plates, a mechanical property testing and material model effort consisting of both strain rate sensitivity and failure surface definition, specific to each plate, is required to accurately predict exit velocities and failure modes.

6. CONCLUSION

An attempt was made to improve impact simulations of 0.25″, 0.14″, and 0.09″ thickness plates without conducting a complete mechanical property testing program and corresponding material model effort. Two simple candidate scaling approaches were used to modify the baseline 0.5″ Ti-6Al-4V material model. Both approaches sought to improve the exit velocity simulations by transforming the baseline model so that it would be a closer match to the mechanical properties of the 0.25″, 0.14″, and 0.09″ thickness plates. Neither scaling approach demonstrated a clear and repeatable pattern of improvement. Other approaches were identified and not fully assessed because they did not create physically realistic mechanical properties. With regard to the three samples for which scaling was attempted, there were three different reasons for the ineffectiveness of the approach. Therefore, an alternate scaling approach, which might prove itself more effective, did not present itself.

The shape of the failure surface was not changed and was only scaled. It is possible adjusting the shape of the failure surface, creating more accurate and generic failure strains, could lead to a single failure surface, which provides a good match to ballistic test data for all four plates. It is also possible that the state of stress-dependent failure strains vary significantly from plate to plate and that a generic representative failure surface does not exist.

It is also possible that the Von-Mises yield surface assumption of compression-tension symmetry, or perhaps isotropic behavior, which is used in *MAT_224, is not sufficiently valid for one or more of the three other thickness plates for accurate predictions to be made. *MAT_224 has been enhanced, which allows the modeling of different compression and tension yield strengths and plastic behavior, and which produces a generalized yield surface (*MAT_224_GYS) [10]. In addition, a new anisotropic material model (*MAT_264), based on *MAT_224, has also been added to LS-DYNA [11]. *MAT_224_GYS and *MAT_264 offer opportunities for matching yield asymmetry and anisotropic plasticity observed in all the Ti-64 plates to varying degrees and may be investigated in future work.

The mechanical properties of the four Ti-6Al-4V plates considered were varied, but within the American Society for Metals specification. The within-specification variability is a result of different chemistry and manufacturing processes, including metal working and heat treatment. Simple modifications to the baseline model, based on tensile data, were not able to compensate for the variability and provide an accurate prediction of the other plate's failure response. This demonstrates that failure is a complex physical phenomenon, and that a truly predictive material model must be a comprehensively accurate representation of the specific mechanical properties of the sample [1].

It is recommended that a comprehensive testing and material modeling procedure [1] be employed when using finite element analysis as a tool in final design and validation. Processing of flight critical hardware needs to be controlled as much as possible to limit the variability of material properties from batch to batch.

7. REFERENCES

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APPENDIX A—MATERIAL COMPARISON OF AMS 4911 TI-6AL-4V PLATES

It is noted that the AMS 4911 Ti-6Al-4V plates, with different thicknesses, have varying mechanical properties. The four Ti-6Al-4V titanium plates (thicknesses of 0.5″, 0.25″, 0.14″, and 0.09″) were commercial off-the-shelf products from different companies. The tensile test data for different strain rates are summarized in figures A-1–A-10 and table A-1. It is worthwhile to emphasize that these plots used the simple formula of equation 1 to convert the force-displacement data to the stress-strain curve. They do not represent the actual true stress versus true strain relations beyond the necking point (see section 3). These plots can be used to compare the material property differences among the plates with different thicknesses.

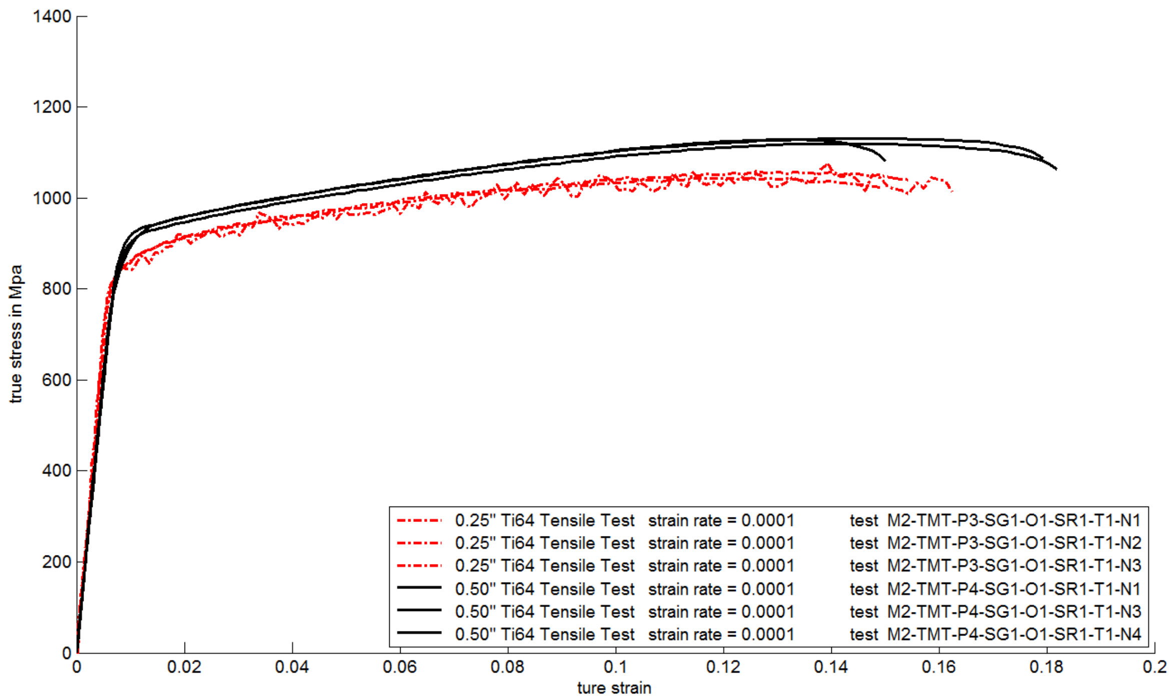

Figure A-1. Stress-strain relation of strain rate = 0.0001 (1/s) for 0.5″ and 0.25″ plate [A-1]

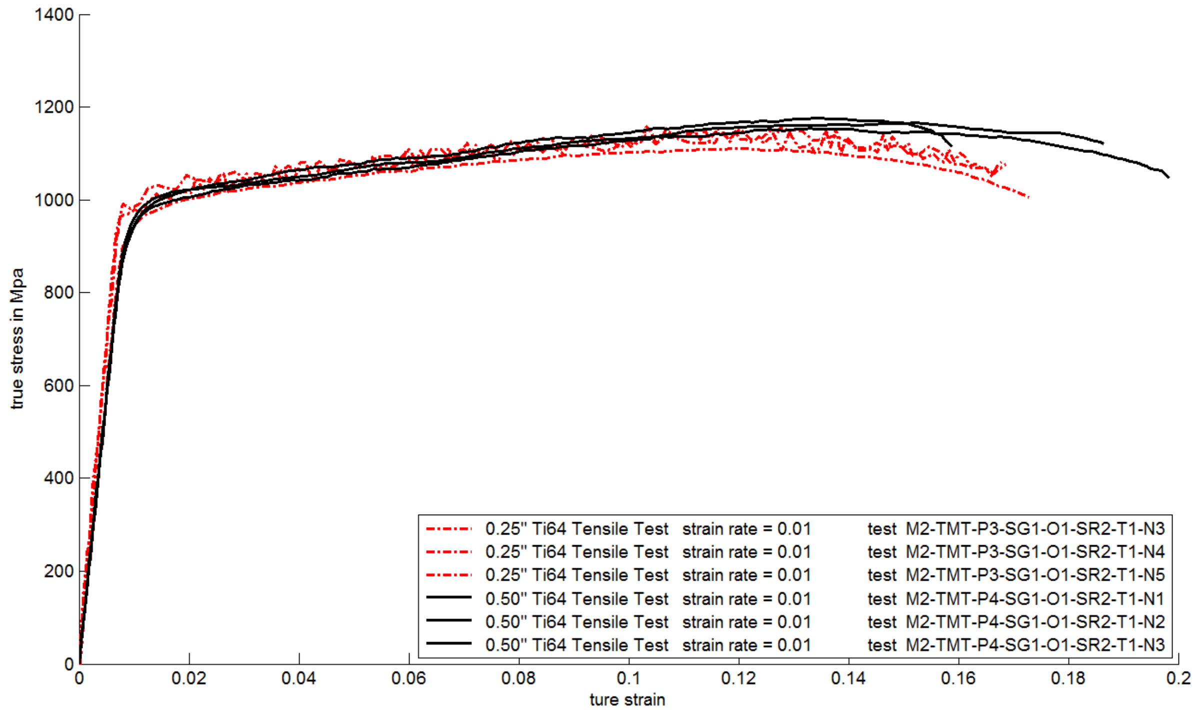

Figure A-2. Stress-strain relation of strain rate = 0.01 (1/s) for 0.5″ and 0.25″ plate [A-1]

Table A-1. Yield strength comparison for plates with different thickness

Plate thickness	Strain Rate	Yield Strength (MPa)
0.5″	0.0001	800
	0.01	900
	1	1100
	500	1300
	1000	1310
0.25″	0.0001	810
	0.01	900
	1	1010
	500	1175
	1000	1220
0.14″	1	1050
	500	1250
0.09″	1	1025
	500	1275

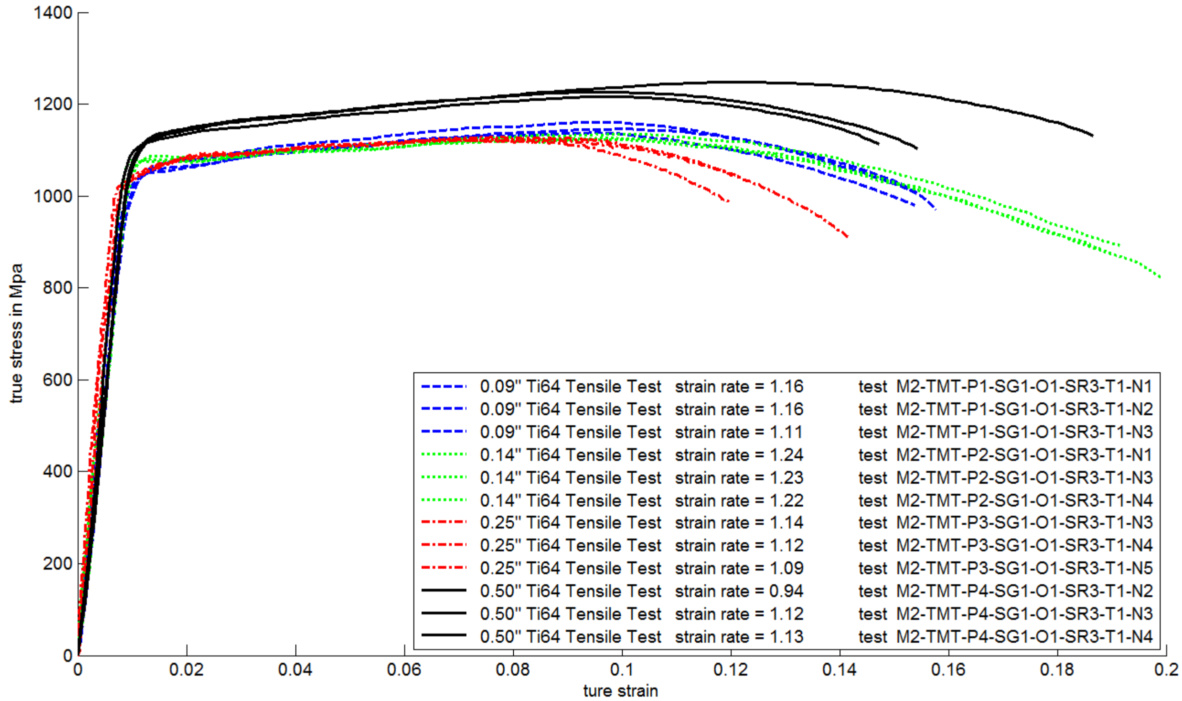

Figure A-3. Stress-strain relation of strain rate = 1 (1/s) for 0.5″, 0.25″, 0.14″, and 0.09″ plate [A-1]

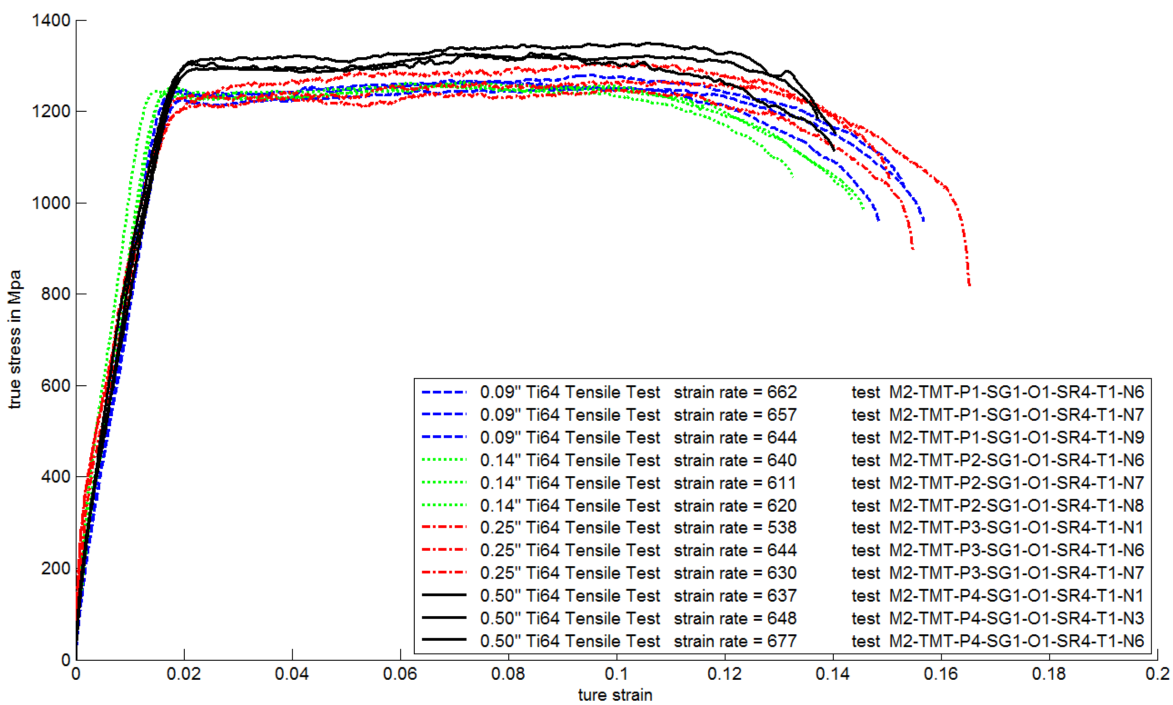

Figure A-4. Stress-strain relation of strain rate = 500 (1/s) for 0.5″, 0.25″, 0.14″, and 0.09″ plate [A-1]

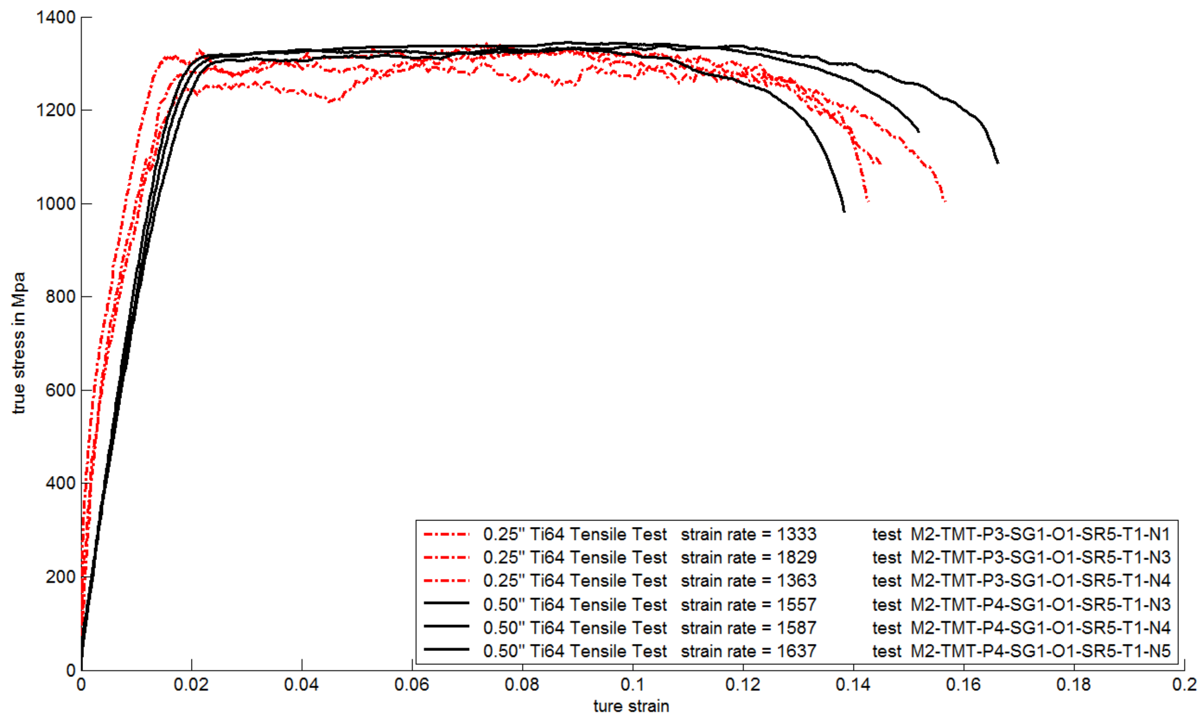

Figure A-5. Stress-strain relation of strain rate = 1000 (1/s) for 0.5″ and 0.25″ plate [A-1]

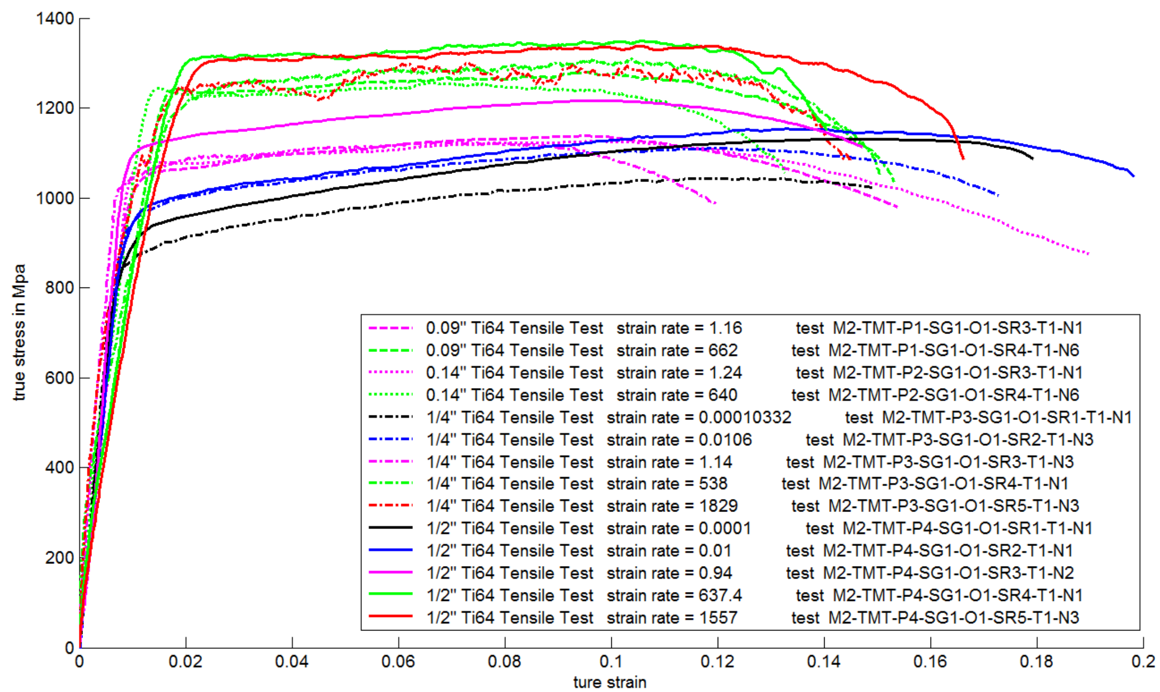

Figure A-6. Stress-strain relation at a glance for all available strain rate of 0.5″, 0.25″, 0.14″, and 0.09″ plate [A-1]

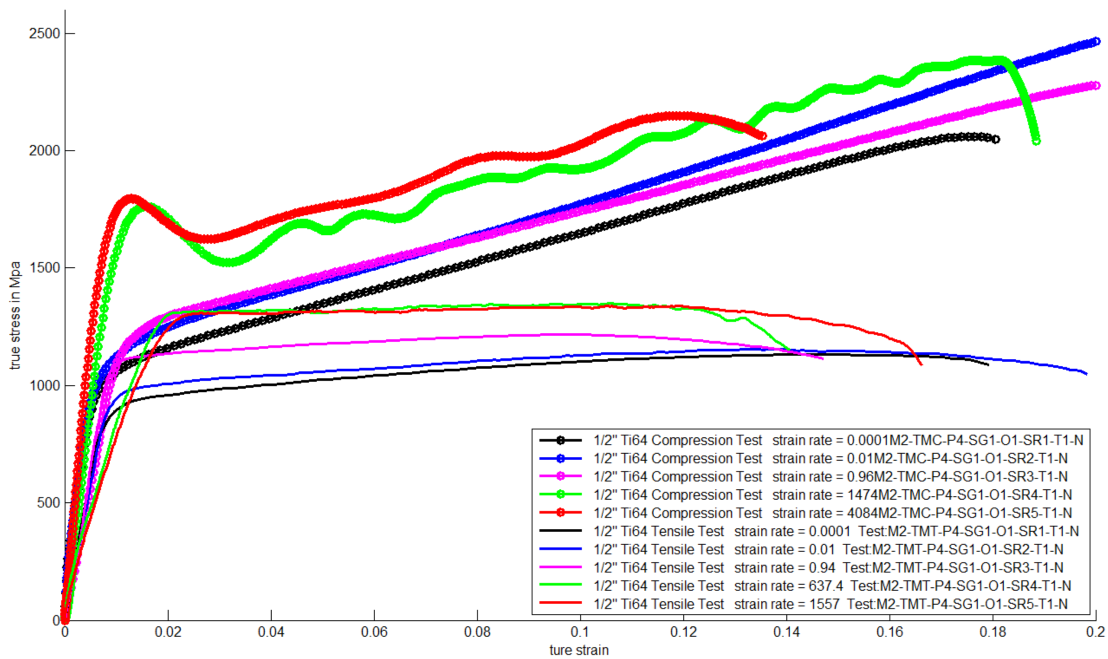

Figure A-7. Stress-strain relation tensile and compression tests for 0.5″ plate [A-1]

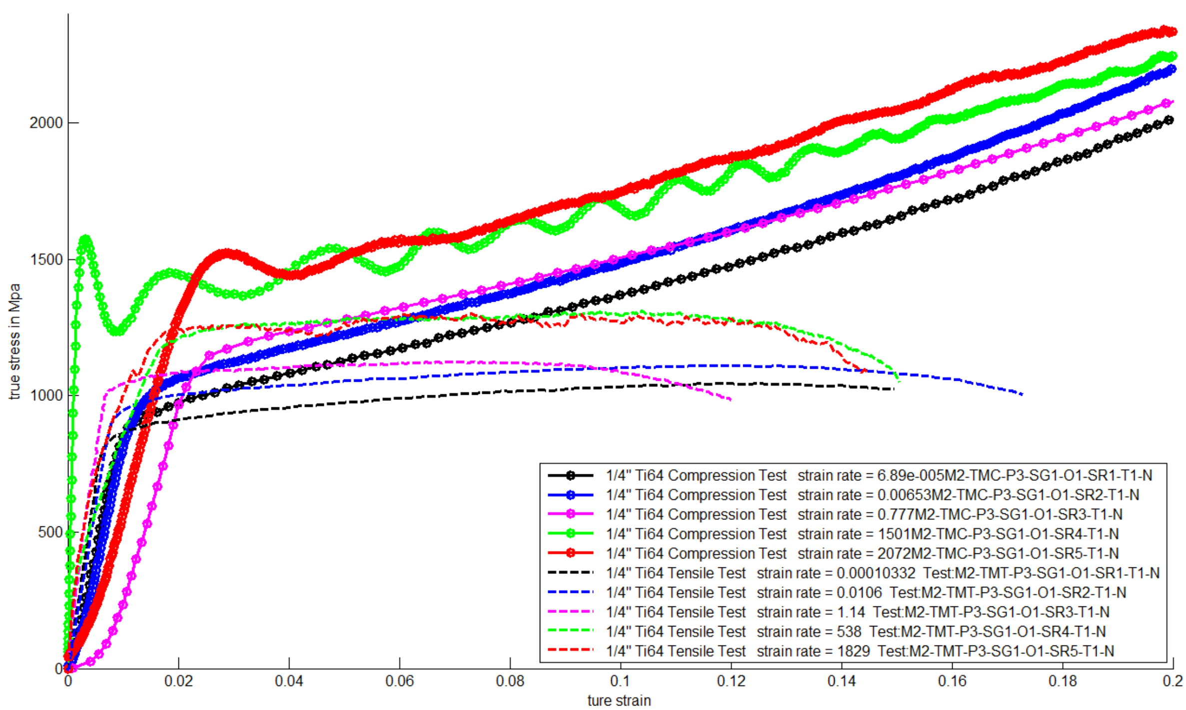

Figure A-8. Stress-strain relation tensile and compression tests for 0.25″ plate [A-1]

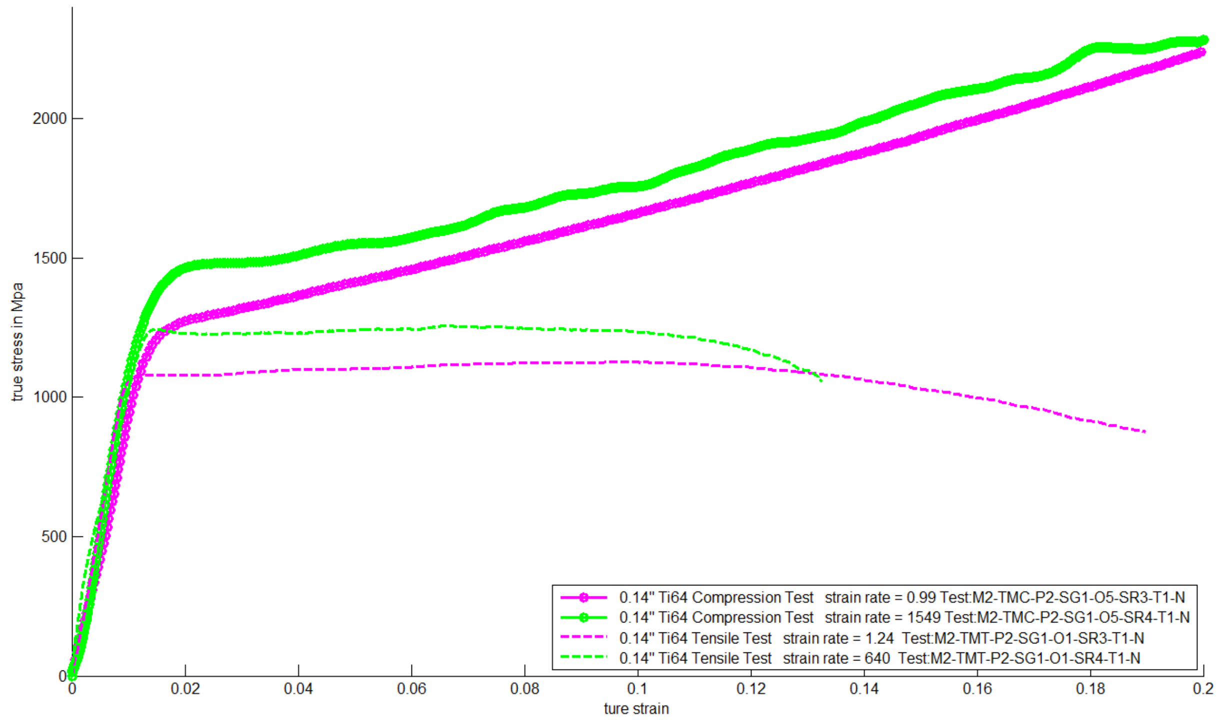

Figure A-9. Stress-strain relation tensile and compression tests for 0.14″ plate [A-1]

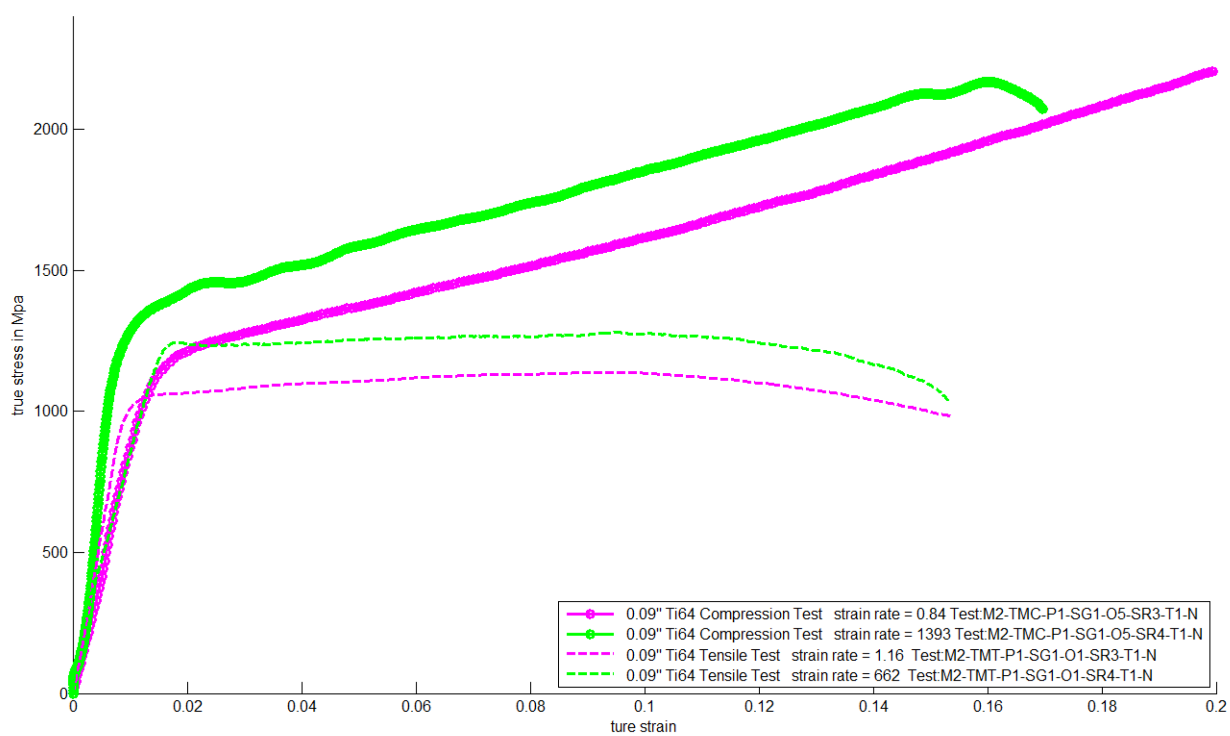

Figure A-10. Stress-strain relation tensile and compression tests for 0.09″ plate [A-1]

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