Modelling Dynamic Behaviour and Spall Failure of Aluminium Alloy AA7010

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Abstract. A finite strain constitutive model to predict the dynamic deformation behaviour of Aluminium Alloy 7010 including shockwaves and spall failure is developed in this work. The important feature of this newly hyperelastic-plastic constitutive formulation is a new Mandel stress tensor formulated using new generalized orthotropic pressure. This tensor is combined with a shock equation of state (EOS) and Grady spall failure. The Hill’s yield criterion is adopted to characterize plastic orthotropy by means of the evolving structural tensors that is defined in the isoclinic configuration. This material model was developed and integration into elastic and plastic parts. The elastic anisotropy is taken into account through the newly stress tensor decomposition of a generalized orthotropic pressure. Plastic anisotropy is considered through yield surface and an isotropic hardening defined in a unique alignment of deviatoric plane within the stress space. To test its ability to describe shockwave propagation and spall failure, the new material model was implemented into the LLNL-DYNA3D code of UTHM’s. The capability of this newly constitutive model were compared against published experimental data of Plate Impact Test at 234m/s, 450m/s and 895m/s impact velocities. A good agreement is obtained between experimental and simulation in each test.

1. Introduction
Orthotropic material is a subset of anisotropic material, where their properties is change when measure from different direction. The familiar example of orthotropic materials is sheet of aluminium alloy formed by squeezing thick sections of metal between heavy rollers. Aluminium Alloy 7010 in temper conditions T7651 has been extensively used as structure components in aero industry due to its high strength and high resistance to stress corrosion cracking and good fracture toughness. The ability to predict finite strain deformation and failure in such materials therefore, becoming more and more important and has attracted attention designer and the user of metal structures for many years [1]. This is a great challenge in understanding the behaviour of these materials from quasi-static to high strain rate regimes as adopted in broad engineering applications [2]. Moreover, there are numerous mechanics of materials issues that have yet to be solved, related to orthotropic elastic and plastic behaviour. Based on this motivation, this work is conducted to develop a constitutive formulation to predict the behaviour of commercial aluminium alloys undergoing large deformation including spall failure.

2. New constitutive formulation
The new hyperelastic-plastic constitutive formulation for orthotropic materials in the finite strain regime is formulated based on the multiplicative decomposition of the deformation gradient $\mathbf{F}$. 
\[ F = F_e \cdot F_p \]  

(1)

where \( F_e \) and \( F_p \) is the deformation gradient representing the elastic and plastic part of deformation [15]. This concept distinguishes the proposed constitutive model from hypoelastic-plastic material models (when elastic strains are small compared to the plastic strains). The intermediate (generally non-Euclidean) configuration corresponds to elastically unloaded material, known as the elastic reference configuration which can be physically obtained by elastic unloading of material (unstressed condition).

The deformation gradients \( F_e \) and \( F_p \) are not uniquely defined because the intermediate configuration is not unique, arbitrary local material rotations can be superposed to intermediate configuration preserving it unstressed condition, therefore making the intermediate configuration non-unique. This issue has been discussed extensively in the [3], [4], [5] and [6] to eliminate the non-uniqueness of this configuration. Using the multiplicative decomposition Equation (1), the associated Green-Lagrange strain tensor \( E \) can be defined as

\[ E = \frac{1}{2}(F^T \cdot F - I) = \frac{1}{2}(C - I) \]  

(2)

where \( C \) refers to the right Cauchy-Green strain tensor. This formulation is uniquely determined except for arbitrary rigid body rotations that are superposed in the intermediate configuration while preserving the unstressed condition. As discovered in [12], the experimental work shows a strong correlation between elastic and plastic material symmetries. Therefore, to resolve the non-uniqueness of the intermediate configuration of this formulation, the isoclinic configuration is adopted in this constitutive formulation.

This unique configuration defines the principal directions of material elastic and plastic orthotropy coincide and are not influenced by inelastic deformation. Symbol (\( \hat{\cdot} \)) is used in this work upon each of kinematic and kinetic variables formulated in the isoclinic configuration [7]. The structural tensors \( M_{ii}|i = 1, 2, 3 \) [8] are introduced in this work to construct the orthotropy symmetric group \( \hat{\vartheta} \) of the new constitutive model. Introduction of the structural tensors \( \hat{M}_{ii}|i = 1, 2, 3 \) in the isoclinic configuration assumes the principal directions of material elastic orthotropy (material symmetry) aligned with the unit (director) vectors \( \hat{n}_1, \hat{n}_2 \) and \( \hat{n}_3 \). As depicted in Figure 1, the structural tensors can be pushed forward from an initial configuration \( \Omega_i \) to elastically unloaded configuration \( \Omega_p \) as \( M_{ii} = F_p M_{ii} F_p^{-1} \).

A triad of unit vectors that represent the material symmetries \( \hat{n}_1, \hat{n}_2 \) and \( \hat{n}_3 \) is presented by two orthogonal axes with arrows in Figure 1. It can be seen that the plastic deformation gradient \( \hat{F}_p \) and \( F_p \) are defined with respect to \( \hat{\Omega}_i \) and \( \Omega_p \) respectively. The elastic part \( F_e \) of the deformation gradient \( F \) contains elastic stretching and rotation. To avoid any rotation to the principal axes of material orthotropy, the plastic rotation \( R_p \) is assigned to \( F_p \). Therefore the principal axes remains fixed or unaltered by plastic deformation in the chosen isoclinic configuration \( \hat{\Omega}_i \).

The rotation and distortion during elastoplastic deformation are contained in the elastic part of \( F \) as a result of isoclinic configuration [9]. It is further emphasized in [9] that the elastic deformation can be compatible with plastic deformation when plastic or elastic deformation is homogeneous. The plastic deformation is assumed incompressible:

\[ \det(F_p) = 1 \]  

(3)
2.1 New Generalised pressure

A new generalised pressure \( \bar{P} \) for orthotropic materials defined in [10] is adopted in the proposed formulation. See for instance [14], [15] and [1], it is proven that this newly orthotropic pressure is capable to produce a good agreement with respect to published experimental data. This generalised pressure is defined as

\[
\bar{P} = -\frac{1}{3} \left( c_{11} + c_{12} + c_{13} \right)^2 + \left( c_{12} + c_{22} + c_{23} \right)^2 + \left( c_{13} + c_{23} + c_{33} \right)^2 \epsilon_v = -3K_{\psi} \epsilon_v
\]  

(4)

where \( c_{ij} \) represent elastic stiffness tensor of orthotropic materials Therefore, the new stress tensor decomposition can be defined as

\[
\bar{\sigma}_{ij} = \sigma_{ij} - \bar{P}_{ij}
\]  

(5)

The parameter \( K_{\psi} \) reduces to the conventional bulk modulus in the limit of material isotropy. \( \psi_{ij} \) which is used defines the direction of the new volumetric axis in stress space then can be defined as

\[
\psi_{(ii)} = \frac{c_{11} + c_{12} + c_{13}}{3} \left( c_{11} + c_{12} + c_{13} \right)^2 + \left( c_{12} + c_{22} + c_{23} \right)^2 + \left( c_{13} + c_{23} + c_{33} \right)^2
\]  

(6)

Using the above formulation, any considered orthotropic materials will uniquely define their own deviatoric plane (yield surface) within the principal stress space. It should be noted that \( \psi_{ij} \) becomes \( \delta_{ij} \) when dealing with isotropic materials.

2.2 New Mandel stress tensor

Mandel stress tensor \( \tilde{\Sigma} \) generally can be defined as

\[
\tilde{\Sigma} = \mathbf{C} \cdot \mathbf{S}
\]  

(7)
The Mandel stress tensor in respect to isoclinic configuration can be defined as follow

\[ \mathbf{\Sigma} = \mathbf{F}_e^T \cdot \mathbf{\tau} \cdot \mathbf{F}_e^{-T} = \det(\mathbf{F}) \cdot \mathbf{F}_e^T \cdot \mathbf{\sigma} \cdot \mathbf{F}_e^{-T} \]  

(8)

The new Mandel stress tensor defined in a deviatoric plane can be defined as

\[ \mathbf{\Sigma}' = \frac{\det(\mathbf{F}) \cdot \mathbf{F}_e^T \cdot \mathbf{\sigma} \cdot \mathbf{F}_e^{-T} - \det(\mathbf{F}) \cdot \mathbf{F}_e^T \cdot \frac{\mathbf{\psi}}{\mathbf{\psi}} \cdot \mathbf{\psi} \cdot \mathbf{F}_e^{-T}}{\mathbf{\Sigma}_p} = \frac{\det(\mathbf{F}) \cdot \mathbf{F}_e^T \cdot \mathbf{\mathbf{\mathbf{S}}} \cdot \mathbf{F}_e^{-T}}{\mathbf{\Sigma}_p} \]  

(9)

where \( \mathbf{\Sigma}_p \) defines the volumetric part (pressure) of the proposed Mandel stress tensor.

2.3 Coupling with Equation of State
An appropriate constitutive formulation intended to describe the anisotropic material response under shock loading should consider strength effect and the equation of state (EOS). Based on this motivation, the proposed formulation in this work is combined with the Mie-Gruneisen EOS.

\[ P_{EOS} = \frac{\rho_0 \alpha^2 \mu \left[ 1 + \left( \frac{\gamma_0 - 1}{2} \right) \mu^2 \right]}{1 - (S_1 - 1) \mu - S_2 \mu^2 - S_3 \mu^3} + (1 + \mu) \cdot \mathbf{r} \cdot \mathbf{E} \quad \text{when } \mu > 0 \]  

(10)

\[ P_{EOS} = \rho_0 \alpha^2 \mu + (1 + \mu) \cdot \mathbf{r} \cdot \mathbf{E} \quad \text{when } \mu < 0 \]  

(11)

where

- \( \mathbf{E} \) is the internal energy per initial specific volume
- \( S_1, S_2, S_3 \) are the coefficients of the slope of the \( U - u_p \) curve
- \( \gamma_0 \) is the Gruneisen gamma for the un-deformed material,
- \( \alpha \) is the first order volume correction to \( \gamma_0 \),
- \( c, S_1, S_2, S_3, \gamma_0, \alpha, \rho_0 \) represent the material properties supplied by the user to characterize this EOS.

2.4 Elastic Free Energy Function
The elastic orthotropy is defined using of the Helmholtz free energy as a function of evolving structural tensors.

\[ \mathbf{Q}_e = \mathbf{Q}_e(\mathbf{\mathbf{\mathbf{F}}}_e, \mathbf{\mathbf{\mathbf{M}}}_{11}, \mathbf{\mathbf{\mathbf{M}}}_{22}) = \mathbf{Q}_e(\mathbf{\mathbf{\mathbf{Q}}} \mathbf{\mathbf{\mathbf{M}}}_e, \mathbf{\mathbf{\mathbf{Q}}} \mathbf{\mathbf{\mathbf{M}}}_{11} \mathbf{\mathbf{\mathbf{Q}}}^T, \mathbf{\mathbf{\mathbf{Q}}} \mathbf{\mathbf{\mathbf{M}}}_{22} \mathbf{\mathbf{\mathbf{Q}}}^T) \]  

(12)

where \( \mathbf{Q} \) is orthogonal rotation tensor.

2.5 Orthotropic Yield Criterion
The yield function used to model the dependence on plastic anisotropy in this formulation is defined using the structural tensors \( \mathbf{\mathbf{\mathbf{M}}}_i \), \( i = 1,2,3 \) of the material symmetry group \( \vartheta \). The Hill’s yield function is adopted to define the plastic anisotropy of the proposed constitutive model.

\[ \dot{f} = \sqrt{\mathbf{\mathbf{\mathbf{H}}}_e : \mathbf{\mathbf{\mathbf{H}}}'_e} = \dot{f}(\alpha) = 0 \]  

(13)

where \( \mathbf{\mathbf{\mathbf{H}}}_e \) refers to a fourth-order tensor defined in the chosen isoclinic configuration \( \mathbf{\mathbf{\mathbf{\Omega}}}_i \). The incremental of flow stress during plastic deformation is defined by \( \dot{f}(\alpha) \) that is controlled by isotropic hardening.
2.6 Evolution Equations

The evolution of the proposed constitutive model is defined using the second law of thermodynamics framework. The formulation can be expressed using the Clausius-Plank inequality as

$$
\mathcal{D} = \dot{\lambda} \left( \sqrt{\Sigma'} : \Sigma' - \alpha : \frac{\partial f}{\partial \alpha} \right) \geq 0
$$

(14)

where $\alpha$ and $\dot{\lambda}$ define isotropic hardening and plastic rate parameter respectively. The plastic multiplier $\dot{\lambda}$ is calculated from the consistency (loading-unloading) condition.

$$
\dot{\lambda} = \frac{\dot{f}_\Sigma : \Sigma^p : \dot{\mathbf{D}}}{-\dot{f}_\alpha : \sqrt{2} \mathbf{K}_f + \dot{f}_\Sigma : \Sigma^p : \text{sym} \dot{\mathbf{r}}}
$$

(15)

The relationship between stress and strain increments is concluded by the elastoplastic tangent modulus $\mathbf{C}_\Sigma$

$$
\mathbf{C}_\Sigma = \mathbf{C}^p + \frac{\left( \mathbf{C}^p : \text{sym} \dot{\mathbf{r}} \right) \otimes \left( \dot{\mathbf{f}}_\Sigma : \mathbf{C}^p \right)}{-\dot{f}_\alpha : \sqrt{2} \mathbf{K}_f + \dot{f}_\Sigma : \mathbf{C}^p : \text{sym} \dot{\mathbf{r}}}
$$

(16)

2.7 Grady Failure Model

Grady spall model known as an energy-based failure model is adopted in the proposed formulation [11]. This model assumes the material spall when the strain energy reaches a certain level. Two mechanisms are investigated in this Grady model, which are brittle and ductile fracture.

$$
p_s (\text{ductile}) = \sqrt{\frac{2 \rho c_0^2 \sigma_y \varepsilon_{\text{fail}}}{\mathbf{C}_\Sigma}} \quad \text{Ductile Failure}
$$

(17)

$$
p_s (\text{brittle}) = \sqrt{\frac{3 \rho c_0 K_c^2 \dot{\varepsilon}}{9 \rho K_c}} \quad \text{Brittle Failure}
$$

(18)

where:
- $\rho$ = density
- $c_0$ = bulk sound speed
- $\sigma_y$ = yield stress
- $\varepsilon_{\text{fail}}$ = Critical strain failure
- $K_c$ = Fracture toughness
- $\dot{\varepsilon}$ = Rate of volumetric dilatation

For a certain strain rate there is a transition point between ductile and brittle spall. This critical strain rate, $\dot{\varepsilon}_{\text{crit}}$ can be calculated from:

$$
\dot{\varepsilon}_{\text{crit}} = \sqrt{\frac{8 B \sigma_y^2 (\sigma_y \varepsilon_{\text{fail}})^3}{9 \rho K_c^4}}
$$

(19)

where:
- $\rho$ = density
- $\sigma_y$ = yield stress
$$\varepsilon_{\text{crit}} = \text{Critical strain failure}$$

$$K_c = \text{Fracture toughness}$$

$$B = \text{Isotropic/kinematic hardening}$$

3. New Material Model Implementation

The proposed constitutive formulation was implemented into DYNA3D finite element code of UTHM’s version and name Material Type 92 referring to the works published in [16] and [17]. It should be noted that this is the first ever algorithm implementation of a newly constitutive formulation performed in the code. As discussed previously, a new generalized pressure is adopted in the proposed formulation. Therefore, few modifications are required to uniquely characterize the DYNA3D of UTHM’s version with the new orthotropic pressure. A new definition of EOS was introduced to the code by decoupling the volumetric parts from the full stress tensor. Equations 17 until 19 are directly adopted for spall model implementation into the code.

4. Numerical Simulation

At this stage, the capability to predict the deformation behaviour under high pressure and shockwave is assessed against the experimental data of Plate Impact test published in [12]. Thus, a set of experiments plate impact test of Aluminium Alloy 7010 was used. The finite element FE model used in this analysis to simulate the Plate Impact test is discussed in this section. Figure 2 shows the configuration used to simulate each Plate Impact test analysis in this work.

![Figure 2 Configuration of the Plate Impact test simulation](image)

It can be seen that the model is divided into three parts of rectangular bars with 4x4 solid elements for its cross section. The PMMA block, specimen and flyer is modelled with 100 solid elements (12mm in length), 75 solid elements (10mm in length) and 25 solid elements (2.5mm in length) respectively. As can be observed, the model orientation is parallel to the impact axis, (Z axis). The mesh applied of this simulation was set to allow a 1D wave propagation along the length of the bars during the impact. From this figure, it is noticed that symmetrical planes were adopted on all sides of the bars. A non-reflecting boundary condition was used to define the back of this block (PMMA), to ensure that no release wave was reflected from the back of the PMMA block into the test specimen. There was a contact interface defined in between the flyer (impactor) and the test specimen. A time history block was prescribed to the elements at the top of PMMA bar to ensure the stress time histories was recorded during impact.
5. Results and Discussion

The Z stress in the top elements of the PMMA bar was compared against the experimental data in short transverse and the longitudinal (rolling) directions of the specimen, performed at three different impact velocities: 234m/s, 450m/s and 895m/s. Table 1 shows the material properties of each parts including the Gruneisen EOS and the Grady failure model adopted in this analysis. The flyer is prescribed as Aluminium 6082-T6 [12].

The results obtained for each impact velocity in respect to both longitudinal and transverse directions are shown in Figures 3 until 8. Referring to the results in the Figures 3 until 8, it can be observed that the proposed Mat92 is capable of describing the elastic-plastic loading-unloading behaviours of the Al7010 since a close prediction is obtained in each test. The comparison between Mat 92 and the experimental data are summarised in Table 2.

| Table 1 Material properties used in the Plate Impact test analysis |
|-----------------|-----------------|-----------------|
| Parameters      | Materials       |                  |
|                 | Al7010 | Al6082 | PMMA |
| Young’s modulus | $E_a$    | 70.6 GPa | –    | –    |
|                 | $E_b$    | 71.1 GPa | –    | –    |
|                 | $E_c$    | 70.6 GPa | –    | –    |
| Poisson’s ratio | $\nu_{ba}$ | 0.342 | –    | –    |
|                 | $\nu_{ca}$ | 0.342 | –    | –    |
|                 | $\nu_{cb}$ | 0.342 | –    | –    |
| Shear modulus   | $G_{bc}$  | 26.31 GPa | 26.8 GPa | 2.3 GPa |
|                 | $G_{ab}$  | 26.48 GPa | 26.8 GPa | 2.3 GPa |
|                 | $G_{ac}$  | 26.48 GPa | 26.8 GPa | 2.3 GPa |
| Yield stress in a – direction | $\sigma_y$ | 564 MPa | 250 MPa | 70 MPa |
| Tangent plastic modulus in a – direction | H | 0.13 GPa | 130 MPa | 300 MPa |
| Pressure cutoff | $p_{cut}$ | – | 2.5 GPa | – |
| Density | $\rho$ | 2.81 gcm$^{-3}$ | 2.7 gcm$^{-3}$ | 1.18 gcm$^{-3}$ |
| Hill’s parameters | $R$ | 1 | – | – |
|                 | $P$ | 0.719 | – | – |
|                 | $Q_{bc}$ | 1 | – | – |
|                 | $Q_{ba}$ | 1 | – | – |
|                 | $Q_{ca}$ | 1 | – | – |
| Gruneisen parameters | $C$ | 5200 ms$^{-1}$ | 5240 ms$^{-1}$ | 2180 ms$^{-1}$ |
|                 | $s_1$ | 1.36 | 1.4 | 2.088 |
|                 | $s_2$ | 0.00 | 0.00 | –1.124 |
|                 | $s_3$ | 0.00 | 0.00 | 0.00 |
|                 | $\Gamma$ | 2.2 | 1.97 | 0.85 |
|                 | $a$ | 0.48 | 0.48 | 0.00 |
| Grady parameters | $\rho$ | 2.81 gcm$^{-3}$ | – | – |
|                 | $c_0$ | 0.52 | – | – |
|                 | $\xi_{fai}$ | 0.5 | – | – |
|                 | $K_e$ | 0.0025 | – | – |
|                 | $B$ | $\rho/c_0^2$ | – | – |
Figure 3  Longitudinal Stress at 234ms$^{-1}$ impact in longitudinal direction

Figure 4  Longitudinal Stress at 234ms$^{-1}$ impact in transverse direction

Figure 5  Longitudinal Stress at 450ms$^{-1}$ impact in longitudinal direction

Figure 6  Longitudinal Stress at 450ms$^{-1}$ impact in transverse direction

Figure 7  Longitudinal stress at 895ms$^{-1}$ impact in longitudinal direction

Figure 8  Longitudinal stress at 895ms$^{-1}$ impact in transverse direction
Table 2 Mat92 vs. Plate Impact Test Data

| Impact Velocity / Direction | Analysis Criteria |
|----------------------------|-------------------|
|                            | HEL (GPa) | Hugoniot Stress Level (GPa) | Pulse (μs) |
| 234ms⁻¹ (Longitudinal):    |           |                             |            |
| Simulation                 | 0.40      | 0.64                        | 1.15        |
| Experiment                 | 0.39      | 0.65                        | 1.65        |
| 234ms⁻¹ (Transverse):      |           |                             |            |
| Simulation                 | 0.40      | 0.64                        | 1.18        |
| Experiment                 | 0.33      | 0.63                        | 1.44        |
| 450ms⁻¹ (Longitudinal):    |           |                             |            |
| Simulation                 | 0.41      | 1.32                        | 1.13        |
| Experiment                 | 0.43      | 1.31                        | 1.16        |
| 450ms⁻¹ (Transverse):      |           |                             |            |
| Simulation                 | 0.38      | 1.28                        | 1.08        |
| Experiment                 | 0.39      | 1.38                        | 1.13        |
| 895ms⁻¹ (Longitudinal):    |           |                             |            |
| Simulation                 | 0.36      | 2.95                        | 1.07        |
| Experiment                 | 0.21      | 3.25                        | 1.10        |
| 895ms⁻¹ (Transverse):      |           |                             |            |
| Simulation                 | 0.32      | 2.89                        | 1.12        |
| Experiment                 | 0.19      | 2.80                        | 1.13        |

In general, the shape of generated pulse shows a good agreement compared to the experimental data. The Hugoniot Elastic Limit (HEL) is described by the initial slope of the longitudinal stress increment. An adequate level of anisotropy of the material is reflected by a different HEL value in each direction. In addition, the generated pulse and the Hugoniot stress levels are closely agreed with the experimental data to confirm the elastic-plastic formulation including the newly implemented orthotropic pressure of the proposed constitutive model is capable to describe the behaviour of orthotropic material undergoing finite strain deformation.

The simulated longitudinal stress at the interface between the target material and PMMA block (recorded in the elements at the back of the specimen), for plate impact at 234ms⁻¹ is presented in Figure 3 and Figure 4. It can be clearly seen that the tensile wave failure or spall (demonstrated by the reloading of the longitudinal stress after the first loading-unloading pulse) is not generated with a lower impact velocity (234ms⁻¹). However, a clear spall criterion can be observed when higher impact velocities (450ms⁻¹ and 895ms⁻¹) are applied.

At 450ms⁻¹ impact velocity, a clear break in slope in the start rising part of trace (HEL) can be seen in a trace as shown in Figure 5 and Figure 6. The value of the HEL shows a slight difference. Specifically, the value in the longitudinal directions are 0.41 GPa and 0.38 GPa, respectively. The associated value obtained in the experiment are 0.39 GPa and 0.33 GPa, respectively. A very close agreement is observed in respect to Hugoniot stress levels. This confirmed the capability of the implemented orthotropic pressure of Mat92 to capture shockwaves in orthotropic materials.

In addition, a clear pull back signals (spall) is developed in both traces; measured 0.31 GPa in the longitudinal and 0.42 GPa in the transverse direction. The values obtained using the Grady’s spall criterion are 0.21 GPa and 0.10 GPa in the longitudinal and transverse directions, respectively. It can be observed the values are smaller than the values in experiment. The constitutive model however, shows sensitivity to the direction of impact. This behaviour is depicted by the point where the spall starts. The similar behaviour is obtained experimentally.

Figure 7 and Figure 8 show the results for 895ms⁻¹ impact velocity. It is clear that the shape of the pulse including the Hugoniot stresses show a good agreement with the experimental data in both impact
directions. This is summarised in Table 2. As observed in 450 ms\(^{-1}\) impact velocity, again the proposed constitutive model predict a smaller pullback signals in impact direction.

Referring to the results, the model as it stands is capable to simulate elastic-plastic, shockwave propagation and spall failure in orthotropic materials of aluminium alloy AA7010. The general pulse shape, the Hugoniot stress level and the EOS are predicted satisfactorily. A higher HEL is observed in the longitudinal direction compared to the short transverse. The Hugoniot stress levels show a very good prediction capability. The pulse shape including the width are in line with the experimental data. The adopted Grady’s spall failure model is obviously capable to predict spall in the materials. However, it must be emphasised that the criterion is not capable to provide a very good accuracy to deal with a complex spall strength evolution developed at different impact velocity. Further works, therefore, are required in both experimental and constitutive modelling aspects.

6. Conclusion

The proposed constitutive model is one of integration between elasticity, plasticity, equation of state (EOS) and spall failure concepts. The formulation is combined with the new stress tensor decomposition defined specifically for orthotropic materials.

The proposed mathematical formulation is implemented into the DYNA3D of UTHM’s version using the suitable stress update algorithm. All parameters defined for the new constitutive model are defined and implemented in detail into the DYNA3D finite element code by modification of several routines in the code.

The final part is a comparison against range of Plate Impact Test data at 234 ms\(^{-1}\), 450 ms\(^{-1}\) and 895 ms\(^{-1}\) impact velocities [12]. A good agreement is obtained in each test. At the end of this work, it can be concluded that the proposed formulation of the new constitutive model has been successfully implemented. The developed formulation is the key novelty of this work that represent shockwave propagation including spall failure of orthotropic materials in a unique alignment of the deviatoric plane within the principal stress space.

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