Response of Cable Harnesses Subjected to High-velocity Impacts

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We compared numerical simulation results obtained using AUTODYN-3D, which is used for impact analysis of complex physical systems including fluid and solid materials, with experimental results obtained using a two-stage light gas gun. The response of electric power supply cable harnesses subjected to high-velocity impact at 4.01 km/s is shown and discussed. In addition, AUTODYN-3D was applied to the numerical simulation of the hypervelocity impact of micrometeoroids and space debris (M/OD) at 15 km/s and 20 km/s, respectively. Material models used in the numerical simulation are also discussed and investigated in order to cover a wide range of impact velocities, including shock-induced vaporization.

Key Words: Discharge, Hydrocode AUTODYN, Two-Stage Light Gas Gun

Nomenclature

\begin{align*}
    &u_p : \text{particle velocity} \\
    &U_s : \text{shockwave in a wide-range region of pressure} \\
    &c_0 : \text{bulk sound speed} \\
    &s : \text{linear slope} \\
    &Y : \text{yield strength} \\
    &\varepsilon : \text{plastic distortion} \\
    &G : \text{elastic modulus} \\
    &p : \text{pressure} \\
    &\rho : \text{density} \\
    &T : \text{temperature} \\
    &\beta : \text{constant} \\
    &_{0} : \text{standardized conditions } (T = 300 \text{ K}, P = 0, \bar{\varepsilon} p = 0) \\
    &_{\text{max}} : \text{maximum value} \\
    &_{\text{ref}} : \text{reference value} \\
    &_{\text{room}} : \text{room condition value} \\
    &j : \text{initial value} \\
    &' : \partial \text{ partial differential quantities at standardized conditions}
\end{align*}

1. Introduction

“Midori II” (development code “ADEOS II”) was launched in 2002 in Japan. However, its operation was terminated in 2003 because of a solar panel malfunction. The failure was putatively caused by electrostatic charge/discharge (ESD). An investigation of the causes and efforts to determine the measures to be taken in the future indicated that verification under as realistic a space environment as possible and enhanced ground tests were necessary. It was presumed that damage to the electrical power cables due to the impact of micrometeoroids and space debris (M/OD) was one of the causes\(^{1,2}\). The electrical power carried by the cables was consistent with the loss of generated power on the satellite. We have been conducting hypervelocity impact tests and numerical simulations in order to build a Japanese design standard that protects satellites from M/OD impacts.

Under those plans, we compared the numerical simulation results with the experimental results and investigated the response of the electric power supply cable harness subjected to high-velocity impacts.

2. Experiments

2.1. Harness cables

M/OD impacts damage exposed harness cables directly and the harness cables inside by penetrating the satellite structure. (1) A harness cable or cables are penetrated or severed by the ejecta from impacts of harness cables. (2) These impacts may lead to short circuits or open circuit failures. (3) The impact on the mission depends on the damaged equipment and redundancy level.

An overview of a harness cable is depicted in Fig. 1. The thickness of the coating, which is made of ETFE, is 150 μm and the average total diameter of the conductor is 0.76 mm. Nineteen electric wires are intertwined to create this conductor.

The harness cables were supplied with voltage and current from an electrical power supply. The voltages were 60 V or 110 V and the respective currents were 2 A or 3 A in our experimental setup. These electrical power conditions are typical in satellites. The signals of the voltage and current of the supply were measured to evaluate the discharge induced by impacts. The configuration of the measurement points is shown in Fig. 2. Half of the harness cables were connected to the return line of the power supply, which means they were connected to the ground. Each hot line and return line is interlaminated.

Experimental examples\(^{3,4,5}\) for various types of electric power supply cables and wire bundles suggested that the
failure mode depends on the damaged equipment and the redundancy level. The failure modes are divided into three broad categories:

1. Lowering of electric power generation: damage to a portion of the harness cables from the solar array system to the power control system
2. Lowering of supply capability: damage to a portion of the harness cables from the power control system to the hardware box
3. Disabling of the electrical power supply: total or ground fault concentrated on part of the harness cables from the solar array system to the power control system or part of the harness cables from the power control system to the hardware box

2.2. Impact tests

A two-stage gas gun was used for impact tests at JAXA’s Sagamihara campus. A photograph of the gun is shown in Fig. 3. The harness cables were placed in a vacuum chamber at the end of the gun. The vacuum pressure was less than 10 Pa. Unusually, the high background pressure did not cause any artifact to the experimental results. Small particles were irradiated perpendicularly to the surface of the harness cables. The materials of the small particles used were glass and alumina as a dielectric, and aluminum and stainless steel as a conductor. These materials are typical of those in space.

The particle diameters were 0.1-0.6 mm because these particles caused significant damage to the satellite and the probability of impact with the satellite was significant. The particle velocity was 3-4 km/s.

The test setup, shown in Fig. 4, demonstrates trilaminar harness cables with an adjacent aluminum plate. This is because we needed to know the impact damage if a particle penetrated the cable harnesses in our experimental setup. Voltage is applied to the surface and to the third layer of the harness cables. The aluminum plate and second layer of the harness were connected to the ground. We also measured the discharge voltages between the electrical cables and the aluminum plate.

One example of the damage is illustrated in Fig. 5. In this study, we detected sustained arc discharge when the particle diameters were larger than 0.3 mm and the particle velocity was about 4 km/s, which was shown by 100 V/3 A electric power supply conditions.

3. Numerical Analysis

3.1. Three-dimensional analytical model

The velocity of M/OD in orbit is above current experimental capabilities. Numerical simulations appear to be the best tool to determine the expected level of damage generated by M/OD on the structural components and instruments of the spacecraft. We obtained numerical simulation results using AUTODYN-3D\textsuperscript{9}, which is used for impact analysis of complex physical systems including fluid and solid materials. As in almost all hydrocodes, so in ANSYS...
3.2.1 Stainless steel (projectile)

The equation of state (E.O.S.) describing the relationship among pressure, density and internal energy (not temperature), ii) the material strength model doing the constitutive relation of solid materials, and iii) the fracture or spallation model mainly for solid materials, but sometimes for the spallation (fracture by negative-pressure) of liquid materials, too. Therefore, in spite of its naming, hydrocodes are formulated in order to simulate the highly dynamic and non-linear behavior of materials in solid and gas phase, as well as in liquid phase, and sometimes even plasma state can be simulated approximately by using appropriate E.O.S (Equation of State).

The purpose of the impact analysis for hypervelocity impact was as follows:

(1) To clarify the damage mechanism in the hypervelocity impact of M/OD
(2) To clarify the impact assessment of damage in the hypervelocity impact by M/OD (impact scars and impact conditions of the damage).

We assumed the condition leading to short circuits or open circuit failure in the response of the electric power supply cable harness and developed three-dimensional analytical models.

Projectiles are assumed spherical and to have the properties of stainless steel, whose diameter is ø0.3 mm for a 4.01 km/s velocity, hitting the target, which is the harness cable surface. Projectiles and harness cables are modeled on the Lagrange solver.

Nineteen electric wires are treated as one electric wire with corrected density and matched total mass conductor.

Three harness cables are coupled transversely and stacked in a trilaminar structure. The back wall of the trilaminar harness cables is a rigid wall and the face of each layer is set as the contact boundary condition. The length of each harness cable is 10 mm and each edge is set as the free boundary condition.

The mesh size of the impact point neighborhood is about 0.03 mm. The mesh size of the harness cables that did not receive any direct hits by projectiles is about 0.15 mm. The mesh size increases with distance from the impact point. The three-dimensional analytical model is shown in Fig. 6.

3.2. Material Properties

3.2.1 Stainless steel (projectile)

The material properties of stainless steel (SS304) are described by the material library of AUTODYN. The equation of state is used with Mie-Grüneisen-type shock Hugoniot. The equation of state is based on the Steinberg-Guinan model [7]. In this model, the yield strength $Y$ and elastic modulus $G$ of von Mises are dependent on the plastic distortion $\varepsilon_p$, the pressure $p$, the density $\rho$, and the temperature $T$, and are given by the following equations:

$$ Y = Y_0 \left[ 1 + \beta_{\rho} \left( \varepsilon_p + \varepsilon_j \right) \right]^3 \left[ 1 + \left( \frac{Y_p}{Y_0} \right) \frac{P}{\rho_0} + \left( \frac{G'}{G_0} \right) \left( T - T_{room} \right) \right] $$

where density $\rho$ is used in $\eta = \rho/\rho_{ref}$, where $\rho_{ref}$ is the reference density. However, the maximum yield strength value $Y_{\text{max}}$ does not exceed a value that is shown by $Y_0 \left[ 1 + \beta_{\rho} \left( \varepsilon_p + \varepsilon_j \right) \right]^3 \leq Y_{\text{max}}$

where $\varepsilon_j$ is the initial plastic distortion and usually $\varepsilon_j = 0$. $T_{\text{room}}$ is room temperature, $Y_0$ and $G_0$ are the yield strength and elastic modulus values, respectively, at standardized conditions ($T = 300$ K, $P = 0$, $\varepsilon_j = 0$), $Y'$ and $G'$, which are variables with subscripts, are partial differential quantities at standardized conditions. $Y_p$, $G_p$, $Y_p/Y_0$, $G_p/G_0$, $\beta_{\rho}$, $n$, and $Y_{\text{max}}$ are determined by each experiment. In addition, $Y_p/Y_0 \approx G_p/G_0$ is known by a number of past experimental results.

The fracture condition is applied to the fracture model by suitability plastic distortion. For this three-dimensional analytical model using the Lagrange solver, we set the “Erosion” function to prevent the calculation meshes from being crushed and the calculation from stopping.

3.2.2 Copper (electrical harness cable core)

The material properties of the electrical harness cable core (Cu-OFHC-19) are described by the material library of AUTODYN. Nineteen electric wires are treated as one electric wire with corrected density and matched total mass conductor. At the same time, the sonic velocity corrected for the copper acoustic impedance (density $\times$ sonic velocity) to assess the validity of the developed pressure. Similar to stainless steel, the equation of state used with shock and the constitutive law is applied to the Steinberg Guinan model. The fracture condition is applied to the fracture model by suitability plastic distortion. We also set the “Erosion” function to prevent the calculation meshes from being crushed and the calculation from stopping.

3.2.3 Teflon (electrical harness cable coating)

The material properties of the electrical harness cable coating (Teflon) are described by the material library of AUTODYN. The equation of state used with shock and the constitutive law is applied to the von Mises model (perfect elastoplasticity model). The fracture condition is applied to the fracture model by negative pressure. We also set the “Erosion” function.
Fig. 7(a). Energy-time history of each material property.

Fig. 7(b). Energy-time history of each material property.

Fig. 8(a). Energy-time history of each harness cable layer.

Fig. 8(b). Energy-time history of each harness cable layer.

Fig. 9(a) Damage of the first layer harness at 15 μs: impact side.

Fig. 9(b) Damage of the first layer harness at 15 μs: back side.

Fig. 9(c) Damage of the first layer harness at 15 μs: impact side.

Fig. 9(d) Contour figure of the plastic distortion of the first layer cable at 15 μs: impact side.
Fig. 10(a) Damage of the second layer harness at 15 µs: impact side.

Fig. 10(b) Damage of the second layer harness at 15 µs: back side.

Fig. 10(c) Damage of the second layer harness at 15 µs: impact side.

Fig. 10(d) Contour figure of the plastic distortion of the second layer cable at 15 µs: impact side.

Fig. 11(a) Damage of the third layer harness at 15 µs: impact side.

Fig. 11(b) Damage of the third layer harness at 15 µs: back side.

Fig. 11(c) Contour figure of the plastic distortion of the third layer cable at 15 µs: back side.

Fig. 11(d) Contour figure of the plastic distortion of the third layer cable at 15 µs: impact side.
3.3. Analytical results

We determined the end of the phenomena based on the energy-time history in this analysis. Figure 7(a) shows the energy-time history of each material property. The unit of energy is Joules. “Int. Energy” is internal energy, “Kin. Energy” is kinetic energy, and “Tot. Energy” is total energy. Figure 7(b) is an enlarged illustration of Fig. 7(a) for 0-2 µs. Figure 8(a) shows the energy-time history of each harness cable layer. Figure 8(b) is an enlarged illustration of Fig. 8(a). The energy-time history change of the first layer and the second layer is clarified by those figures.

In this direct hit case, the first layer of cables is cut and the core of the second layer becomes exposed on the coating surface. The third layer shows little damage and the plastic distortion of the cable core is less than 0.1 percent. Figures 9(a)–10(c) show the damage of the first layer harness at 15 µs, which is the end time. The grid in Fig. 9(c) shows the dimensions and the unit is millimeters. Figure 9(d) shows the contour figure of the plastic distortion of the first layer of the cable core at 15 µs, which is the end time. The unit of the distortion is dimensionless. Therefore, the maximum contour scale of 0.5 is shown as 50 percent. Figure 10(a)–(c) shows the damage to the second layer of the harness at 15 µs. Figure 10(d) shows the contour figure of the plastic distortion of the second layer of the cable core at 15 µs. Figure 11(a), (b) shows the damage to the third layer of the harness at 15 µs.

These results accurately correspond to the experimental results under the same conditions. In Fig. 8(a) and (b), the first layer of the harness absorbs most of the energy and thus the second layer and the third layer are subjected to little impact.

4. Hypervelocity Impact

4.1. Three-dimensional analytical model

Maximum M/OD on-orbit impact velocity is expected to be around 10 km/s or greater. This velocity is well above current experimental capabilities. For this reason, numerical simulations appear to be the best tool to determine the expected level of damage generated by M/OD on the structural components and instruments of the spacecraft. Presented here are the results of the analysis of the hypervelocity impact of M/OD on the electric power supply cable harness at 15 km/s and 20 km/s.

We used the same three-dimensional analytical models as those used in Chapter 3. The mesh size of the impact point neighborhood is about 0.02 mm. The mesh size of the harness cables that did not receive any direct hits by projectiles is about 0.15 mm. The mesh size increases with distance from the impact point.

4.2. Material properties

4.2.1 Alumina (projectile)

We assumed that the material of the space debris is alumina. The material properties of alumina (Al2O3-99.7) are described by the material library of AUTODYN. The equation of state used with the polynomial model and the constitutive law and the fracture law is applied to the Johnson-Holmquist model. We also set the “Erosion” function.

4.2.2 Dolomite (projectile)

We assumed that the material of the micrometeoroids is dolomite. Dolomite is the name of a sedimentary carbonate rock and a mineral, both composed of calcium magnesium carbonate CaMg(CO3)2 found in crystals. The material
properties of dolomite are described in Ref. 8. The equation of state is used with the Tillotson model\(^9\). The constitutive law does not apply and the fracture condition is applied to the fracture model by negative pressure. We also set the “Erosion” function.

4.3. Hypervelocity impact results

We determined the end of the phenomena based on the energy-time history in this analysis. In each direct hit, the first layer of the cable is cut and the second layer shows damage, but does not become exposed on the coating surface. Figure 12(a) shows the cross-sectional view of the damage to the cable harness at 1.2 \(\mu\)s, which is the end time when the space debris is assumed to be alumina. Figures 12(b)–(d) show the damage to each layer of the harness at 1.2 \(\mu\)s. The particle diameter was 0.3 mm and the particle velocity was 15 km/s. Figure 13(a) shows the cross-sectional view of the damage of the cable harness at 1.2 \(\mu\)s, which is the end time in the case of the micrometeoroids. Figure 13(b)–(d) shows the damage to the second layer of the harness at 1.2 \(\mu\)s, which is the end time when the micrometeoroids are considered to be dolomite. The particle diameter was 0.3 mm and the particle velocity was 20 km/s.

The first layer of the harness absorbs most of the energy and thus the second layer is subjected to little impact. We did not confirm the condition leading to short circuits or open circuit failure in the response of the electric power supply cable harness in this hypervelocity impact analysis. However, we did verify the effect of the impact of particles larger than 0.3 mm in diameter at hypervelocity on the electric power supply cable harness by experimental results.

5. Summary

Electrical performance degradation was evaluated as an effect of the impact of particles smaller than 0.2 mm in diameter at hypervelocity on the electric power supply cable harness provided with a power supply.

The analytical results accurately correspond to the experimental results when the particle diameters were larger than 0.3 mm and the particle velocity was about 4 km/s.

We did not confirm the threshold value of particle diameter leading to short circuits or open circuit failure in the response of electric power supply cable harnesses at a 15 km/s and 20 km/s hypervelocity impact analyses. We verified the effect of the impact of particles larger than 0.3 mm in diameter at hypervelocity on the electric power supply cable harness.

Acknowledgments

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References

2) Kawakita, S., et al.: Discharge of Spacecraft Solar Panels by Hypervelocity Impact, Transactions of Space Technology Japan, 7 Issue 2s26, (2009), pp. Tr. 2.53-Tr. 2.56

Appendix

Material property

Stainless steel (projectile)

<table>
<thead>
<tr>
<th>Equation of state</th>
<th>Shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference density ($\rho_{\text{ref}}$) (g/cm³)</td>
<td>7.9</td>
</tr>
<tr>
<td>Grüneisen coefficient ($\Gamma$)</td>
<td>1.93</td>
</tr>
<tr>
<td>Bulk sound speed ($c_{\text{b}}$) (m/s)</td>
<td>4570</td>
</tr>
<tr>
<td>Linear slope ($s$)</td>
<td>1.49</td>
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</tbody>
</table>

Constitutive law (Steinberg-Guinan)

- Elastic modulus ($G$) (GPa) | 77 |
- Yield strength ($Y$) (MPa) | 340 |
- Maximum yield strength ($Y_{\text{max}}$) (MPa) | 2500 |
- Work hardening coefficient ($\beta_{\text{w}}$) | 43 |
- Work-hardening exponent ($n$) | 0.35 |
- Slope $dG/dp$ ($G_{\text{r}}/G_{\text{r}}$) (MPa) | 1.74 |
- Slope $dG/dT$ ($G_{\text{r}}/G_{\text{r}}$) (MPa) | 35.04 |
- Slope $dY/dp$ ($Y_{\text{r}}/Y_{\text{r}}$) | 7684 x 10^-3 |
- Fracture condition | Plastic |
- Fracture strain (%) | 30 |
- Erosion condition | Geometric |
- Erosion strain (%) | 200 |

Teflon (electrical harness cable coating)

<table>
<thead>
<tr>
<th>Equation of state</th>
<th>Shock</th>
</tr>
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<tr>
<td>Reference density ($\rho_{\text{ref}}$) (g/cm³)</td>
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<tr>
<td>Grüneisen coefficient ($\Gamma$)</td>
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<td>Bulk sound speed ($c_{\text{b}}$) (m/s)</td>
<td>1340</td>
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<tr>
<td>Linear slope ($s$)</td>
<td>1.93</td>
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</tbody>
</table>

Constitutive law (von Mises)

- Elastic modulus ($G$) (GPa) | 2.33 |
- Yield strength ($Y$) (MPa) | 50 |
- Fracture condition | Hydro (Pn) |
- Hydro Tensile Limit (GPa) | -1.0 |
- Erosion condition | Geometric |
- Erosion strain (%) | 200 |

CU-OFHC-19 (electrical harness cable core)

<table>
<thead>
<tr>
<th>Equation of state</th>
<th>Shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference density ($\rho_{\text{ref}}$) (g/cm³)</td>
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<tr>
<td>Grüneisen coefficient ($\Gamma$)</td>
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<td>Bulk sound speed ($c_{\text{b}}$) (m/s)</td>
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<td>Linear slope ($s$)</td>
<td>1.489</td>
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</table>

Constitutive law (Steinberg-Guinan)

- Elastic modulus ($G$) (GPa) | 47.7 |
- Yield strength ($Y$) (MPa) | 120 |
- Maximum yield strength ($Y_{\text{max}}$) (MPa) | 640 |
- Work hardening coefficient ($\beta_{\text{w}}$) | 36 |
- Work-hardening exponent ($n$) | 0.45 |
- Slope $dG/dp$ ($G_{\text{r}}/G_{\text{r}}$) (MPa) | 1.35 |
- Slope $dG/dT$ ($G_{\text{r}}/G_{\text{r}}$) (MPa) | -17.98 |
- Slope $dY/dp$ ($Y_{\text{r}}/Y_{\text{r}}$) | 3.396 x 10^-3 |
- Fracture condition | Plastic |
- Fracture strain (%) | 50 |
- Erosion condition | Geometric |
- Erosion strain (%) | 200 |

Alumina (AL203-99.7)

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<tr>
<td>coefficient ($B_{\text{r}}$)</td>
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<tr>
<td>coefficient ($D_{\text{r}}$)</td>
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<td>coefficient ($E_{\text{r}}$)</td>
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<td>coefficient ($F_{\text{r}}$)</td>
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<tr>
<td>coefficient ($H_{\text{r}}$)</td>
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Constitutive law (Johnson-Holmquist)

- Elastic modulus ($G$) (GPa) | 135 |
- Model Type | Continuous (2012) |
- Yield Elastic Limit (GPa) | 5.9 |
- Intact Strength Constant ($A$) | 0.5 |
- Intact Strength Exponent ($N$) | 6.3705 |
- Strain Rate Constant ($C$) | 0.8 |
- Fractional Strength Constant ($D$) | 0.77 |
- Fractional Strength Exponent ($M$) | 1.0 |
- Max. Fracture Strength Ratio | 0.5 |
- Fracture condition | Johnson-Holmquist |
- Hydro Tensile Limit (MPa) | 280 |
- Model Type | Continuous (2012) |
- Damage Constant ($D_{\text{c}}$) | 0.01 |
- Damage Constant ($D_{\text{c}}$) | 1.8 |
- Bulking Constant ($G$) | 1.8 |
- Damage Type | Gradual (JH2) |
- Tensile Failure | Hydro-Pn |
- Erosion condition | Geometric |
- Erosion strain (%) | 200 |

Dolomite (projectile)

<table>
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<th>Equation of state</th>
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<tr>
<td>Reference density ($\rho_{\text{ref}}$) (g/cm³)</td>
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</tr>
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<td>$A$ (GPa)</td>
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<td>$B$ (GPa)</td>
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<td>$a$</td>
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<td>$T_{\text{c}}$ (K)</td>
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<td>Specific heat (kJ/g)</td>
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Constitutive law (None)

- Fracture condition | Hydro-Pn |
- Hydro Tensile Limit (MPa) | 0.0 |
- Erosion condition | Geometric |
- Erosion strain (%) | 200 |