The Influence of Material Matching and Rail Irregularities on Hypervelocity Gouging

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Abstract. Gouging is a phenomenon of large non-linear deformations which may lead a permanent damage on a rocket-sled system. To analyze how gouging occurs and tracing of its development with different matching and rail irregularities, the influences of material matching and rail irregularities on hypervelocity gouging are studied by MPM algorithm in this paper. 5 sets of material matching and 5 set of rail irregularities cases have been simulated in this paper. The results show that gouges would be easier to occur with a lower yield strength material or a rail with irregularities. These results can help us find the methods to avoid gouging.

Keywords. Gouging, material point method, large deformations.

1. Introduction

Gouging damage has been happened in the rails of rail guns, rocket sled rails and two-stage gun barrels. This phenomenon has been studied for many years. Gerstle \cite{1} pointed out that gouging is a phenomenon caused by high thermodynamics. Barber and Bauer \cite{2} argued that there was a threshold velocity for hypervelocity gouging. Mixon \cite{3} has summed up the influence factors that induced gouges, such as, a high slider velocity, a high stress caused by dynamic loading, irregularities on the surface of the rails, and so on. Many other researchers have also studied gouging using laboratory gouging tests \cite{6-8}. As experimental works will take a high cost on the research of gouging, some simulations have been studied in this field either, such as the parallel impact thermodynamics (PIT) model via CTH \cite{9-15} and models via material point method \cite{16}. Previous studies examined the numerical modeling of gouging via CTH, which was developed by Sandia National Laboratory and is not an open code. Therefore, we must study the numerical modeling of gouging using other methods.

A 3D model of simulating gouging has been made with MPM algorithm to analyze the process of gouging happened in a hypervelocity rocket sled rail system by Zhang \cite{16}. She has just analyzed the influence of temperature effects, horizontal velocity, vertical velocity and friction coefficient on the formation of hypervelocity gouging yet. In this paper, we will continue to analyze the influence of material matching and rail irregularities on hypervelocity gouging.

2. MPM Algorithm

The steps of the MPM algorithm can be described as follows: Firstly, the analyzed structure is separated into a finite number of material points and every point carries the whole material parameter information. Secondly, generate a background grid on the basis of computational regions. Thirdly, transfer the material’s information from the material points to the background grid nodes with a series of suitable
shape functions. Then, solve the forces of background grid nodes and impose the boundary conditions on the grid nodes. Fifth, solve the equations of the momentum on the background grid nodes. After the fifth step, transfer the results back to the material points with the suitable shape functions and the state variables of material points, such as velocity, position will be updated. Solve the strain and vortex increments of material points and update the stress and density of every material points either. Finally, abandon the deformed background grid and generate a new background grid.

3. Gouging Numerical Simulation Modeling by MPM

A simplified three-dimensional model of the slider-rail system is applied in this paper which is shown in figure 1. The material of the rail is 1080 steel and the material of the slider is vascoMax300 during the following sections if there is no specifically mentioned. The bottom of the rail is fixed and the velocity of the slider is 3400 m/s.

![Figure 1. Simplified three-dimensional model of the slider-rail system using the MPM.](image)

As Johnson-Cook constitutive model can show the effects caused by thermal softening, it is suitable for the process of gouging phenomenon and will be used during the entire article. The material parameters of the rail and slider are shown in table 1. Meanwhile, the sizes of the rail and slider are shown in table 2.

| Material parameters | Rail (1080 steel) | Slider (vascoMax300) |
|---------------------|-------------------|---------------------|
| \( \rho \) [kg/m\(^3\)] | 7850 | 8000 |
| \( E \) [GPa] | 202.8 | 180.7 |
| \( v \) | 0.27 | 0.283 |
| \( A \) [MPa] | 525 | 2170 |
| \( B \) [MPa] | 3590 | 124 |
| \( n \) | 0.67 | 0.37 |
| \( C \) | 0.029 | 0.03 |
| \( m \) | 0.75 | 0.8 |
| \( T_{\text{melt}} \) [K] | 1670 | 1685 |
| \( T_{\text{room}} \) [K] | 30 | 30 |
| \( c_0 \) [m/s] | 4160 | 3980 |
| \( s \) | 1.195 | 1.58 |
| \( y_0 \) | 1.63 | 1.6 |
Table 2. Geometric parameters.

| Geometry parameters | Rail | Slider |
|---------------------|------|--------|
| Length in x direction [mm] | 100  | 16     |
| Width in y direction [mm] | 16   | 14     |
| Height in z direction [mm] | 16   | 8      |

During the process of simulating gouges by MPM, the background grid size is 1 mm. The space between every two material points is 0.5 mm. The friction coefficient between the rail and the slider is 0.2. The influences of material matching and rail irregularities on gouging’s occurrence and development will be studied in the following sections.

4. Results and Discussion

4.1. Material Matching

The influences of material matching on gouging’s occurrence and development are analyzed in this section. 5 sets of materials are matched in this part and the specific cases are shown in table 3.

Table 3. Slider-rail material matching.

| Case | Slider          | Rail            |
|------|-----------------|-----------------|
| 1    | vascoMax300     | 1080 steel      |
| 2    | vascoMax300     | Armco iron      |
| 3    | vascoMax300     | vascoMax300     |
| 4    | 1080 steel      | 1080 steel      |
| 5    | Armco iron      | 1080 steel      |

The materials of the slider are vascoMax300 in cases 1, 2 and 3 and the materials of the rail are vascoMax300, 1080 steel and armco iron. Compared these cases and the results of the gouges occurred on the rail slice along y=0 are shown in figure 2. The values of gouges occurred on the rail slice are shown in table 4.

Figure 2. The results of gouges occurred on the rail slice along y=0.
Table 4. The values of gouges occurred on the rail slice along y=0.

| Case | Length [mm] | Depth [mm] |
|------|-------------|------------|
| 1    | 23.07       | 1.82       |
| 2    | 32.96       | 4.53       |
| 3    | 4.27        | 0.11       |

The materials of the rail are 1080 steel in cases 1, 4 and 5 and the materials of the slider are vascoMax300, 1080 steel and armco iron. Compared these cases and the results of the gouges occurred on the rail slice along y=0 are shown in figure 3. The values of plastic deformations of the rail slice are shown in table 5.

Figure 3. The results of the gouges occurred on the rail slice along y=0.

Table 5. The values of gouges occurred on the rail slice along y=0.

| Case | Length [mm] | Depth [mm] |
|------|-------------|------------|
| 1    | 23.07       | 1.82       |
| 2    | 22.09       | 1.53       |
| 3    | 21.51       | 0.79       |

Figure 2, figure 3 and table 4 and table 5 indicate that if the rail’s material has a higher strength and yield stress than the slider’s material, the plastic deformations caused by gouging phenomenon will be decreased. However, if the strength and the yield stress of the slider are too low, the slider will has a large plastic deformation which may lead a failure of the task that the slider should accomplish. Hence, we should take the right materials of the slider and the rail to decrease the phenomenon of gouging and ensure to complete the task.

4.2. Rail Irregularities

The influences of rail irregularities on gouging’s occurrence and development are studied in this section. The model of simulating rail irregularities is shown in figure 4 and the size of the irregularities are 0.1 mm- 0.5 mm with a 0.1 mm increasement.
The size of the gouging on the rail is shown in table 6.

**Table 6.** The values of gouges occurred on the rail slice along \( y=0 \).

| Irregularity [mm] | Length [mm] | Depth [mm] |
|-------------------|-------------|------------|
| 0.1               | 41.16       | 3.75       |
| 0.2               | 37.19       | 3.21       |
| 0.3               | 40.30       | 3.81       |
| 0.4               | 38.00       | 3.82       |
| 0.5               | 38.28       | 3.82       |

Table 6 indicates that rail irregularities have greater effects on inducing the phenomenon of gouging, although the plastic deformations caused by gouging tend to be stable with the increasing of rail irregularities. Due to the strong impact between the slider and the irregularity on the rail, the local temperature of the impact position rise up rapidly which will bring the softening effects. The plastic deformation is small when the irregularity is 0.2 mm which is inconsistent with the trend of change. The reason of this appearance should be analyzed in the further works.

**5. Conclusion**

In this paper, the influences of material matching and rail irregularities on hypervelocity gouging are studied by a 3D model based on MPM algorithm. The results show that both of the factors of the material matching and rail irregularities have great effects on inducing the phenomenon of gouging. Meanwhile, the analysis results can help us find the way to suppress the gouging phenomenon to reduce the loss caused by gouges, such as, we should choose the suitable materials of the slider and rail, or we can spray suitable coatings that have low friction coefficient on the track and slider. Besides, the irregularity should be small enough to prevent gouging from occurring.

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**References**

[1] Gerstle F P 1968 *The Sandia Rocket Sled Rail and Slipper Study* Sandia National Labs. Albuquerque NM 22 Aug.

[2] Gerstle F P 1972 *Deformation of Dry Steel Surfaces during High-Velocity Sliding Contact* School of Engineering Duke Univ. Durham NC June.

[3] Gerstle F P, Follansbee P S, Pearsall G W and Shepard M L 1973 Thermoplastic shear and fracture of steel during high-velocity sliding *Wear* **24**(1) 97–106.
[4] Barber J P and Bauer D P 1982 Contact phenomena at hypervelocities Wear 78(1–2) 163–169.
[5] Mixon L C 1997 Assessment of Rocket Sled Slipper Wear/Gouging Phenomena Applied Research Associates Albuquerque, NM.
[6] Tarcza K R and Weldon W F 1997 Metal Gouging at Low Relative Sliding Velocities Wear 209(1–2) 21–30.
[7] Tarcza K R 1995 The Gouging Phenomenon at Low Relative Sliding Velocities Department of Mechanical Engineering Univ. of Texas at Austin TX Dec.
[8] Ramjaun D, Kato I, Takayama K and Jagadeesh G 2003 Hypervelocity impacts on thin metallic and composite space debris bumper shields AIAA Journal 41(8) 1564–1572.
[9] Barker L M, Trucano T G and Munford L W 1987 Surface Gouging by Hypervelocity Sliding Contact Sandia National Labs Sept.
[10] Tachau R D M 1991 An Investigation of Gouge Initiation in High-Velocity Sliding Contact Sandia National Labs Sept.
[11] Schmitz C P, Palazotto A N and Hooser M 2001 Numerical Investigation of the Gouging Phenomena Within a Hypersonic Rail-Sled Assembly AIAA 2001-1191.
[12] Szmerekovsky A G 2004 The Physical Understanding of the Use of Coatings to Mitigate Hypervelocity Gouging Considering Real Test Sled Dimensions Department of Aeronautics and Astronautics Air Force Inst. of Technology Wright-Patterson AFB Dayton OH.
[13] Szmerekovsky A G and Palazotto A N 2015 Structural dynamics considerations for a hydrocode analysis of hypervelocity test sled impacts AIAA Journal 44(6) 1350–1359.
[14] Szmerekovsky A G, Palazotto A N and Baker W P 2006 Scaling numerical models for hypervelocity test sled slipper-rail impacts International Journal of Impact Engineering 32(6) 928–946.
[15] Szmerekovsky A G, Palazotto A N and Ernst M R 2004 Numerical Analysis for a Study of the Mitigation of Hypervelocity Gouging AIAA 2004-1922, April.
[16] Zhang J J 2019 The study of hypervelocity gouging based on the material point method IEEE Transactions on Plasma Science 1-11.