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Gouge Initiation in High-Velocity Rocket Sled Testing

by
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Abstract

A model is presented which describes the formation of surface damage "gouging" on the rails that guide rocket sleds. An unbalanced sled can randomly cause a very shallow-angle, oblique impact between the sled shoe and the rail. This damage phenomenon has also been observed in high-velocity guns where the projectile is analogous to the moving sled shoe and the gun barrel is analogous to the stationary rail. At sufficiently high velocity, the oblique impact will produce a thin hot layer of soft material on the contact surfaces. Under the action of a normal moving load, the soft layer lends itself to an anti-symmetric deformation and the formation of a "hump" in front of the moving load. A gouge is formed when this hump is overrun by the sled shoe. The phenomenon is simulated numerically using the CTH strong shock physics code, and the results are in good agreement with experimental observation.

1.0 Introduction

Surface damage resulting from high-velocity sliding contact has been observed on the rails of rocket sleds, and in the barrels of high-velocity guns (Graff and Dettloff, 1969, 1970; Susoeff and Hawke, 1987; Tachau, 1987; Barker, Trucano, and Susoeff, 1988). The phenomenon is generally referred as "gouging" and can be described as a local scarring of the stationary surface (guider) resulting from the intermittent contact with a high-velocity object (slider) sliding over its surface. The damage area is typically a shallow crater in the shape of a tear-drop as shown in Fig. 1. The leading edge is characterized by the wider end and a slightly raised lip as sketched in Fig. 2.

In the case of rocket sleds (Tachau, 1987), experience has shown that rail gouging begins to occur as the sled accelerates through a velocity of approximately 1,500 m/sec. At velocities below this threshold, there is evidence of sliding contact between the rail and

the rocket sled shoes (slider), but no gouges are created. At velocities above 1,500 m/sec, the sliding contact frequently, but not always, results in the formation of gouges. In high-velocity guns, the slider (projectile) is much smaller and the barrel (guider) alignment is more precise than the alignment of sled track rails. The net effect for the gun is a significantly higher gouge initiation velocity (approximately 3.5 km/sec, Barker et al, 1988). Nevertheless, the gouging damage from the rocket sled and the high-velocity gun have the same characteristics.

Gouging is not a newly discovered phenomenon. It has been observed in rocket sled testing for more than 30 years (Preston, 1964). In the past, rail gouging that resulted from rocket sled testing was regarded an operational nuisance and an unfortunate side effect of high-velocity testing. Repairs typically involved manually grinding down the rough edges. In severe cases, the gouges were filled (using an arc-welder) with new material before grinding. However, it is the by-products of gouging, known as ejecta, that appear to have caused significant damage to a high-velocity rocket sled during a February 1986 reverse ballistic test at Sandia National Laboratories (SNL) rocket sled track (SNL, 1986; Tachau, 1987). Damage to the rocket motor resulted in catastrophic failure of the sled and severe damage to a portion of the track and foundation. In gas guns and railguns, gouging damage to the barrel results in time consuming and costly repairs and maintenance. Aside from the obvious short-term consequences of gouging damage, the viability of high-velocity rocket sled testing, and any other operation involving high-velocity sliding contact, is dependent on resolution of the problems associated with the gouging phenomenon.

An experimental investigation into the problem was carried out by Trott (1967), Graff and Dettloff (1969, 1970). They reported that the formation of gouges appeared to be an unpredictable random phenomenon. The gouging problem was also analytically

studied by several authors modeling the sliding contact as a moving load on a half space (Cole and Huth, 1958; Gerstle and Pearsall, 1974) or as a moving load along an elastic beam on Winkler foundation (Criner and McCann, 1953; Kenney, 1954; Florence, 1956; Adler and Reismann, 1974). However, none of the above quoted studies have provided a satisfactory explanation of the phenomenon.

Recognizing the localized nature of the surface damage, Barker, Trucano, and Susoeff (1988) and Barker, Trucano, and Munford (1987) proposed that the gouge was initiated at a point (or points) where a small asperity on the surface of the guider was impacted by the moving slider. The authors demonstrated numerically by applying the CSQ hydrocode (Thompson, 1979) that a small but extremely high-pressure zone between the contact surfaces was generated by the impact of slider with the asperity and, the high-pressure deformed the parallel surfaces which impinged on each other in a continuous interaction that produced a gouge as depicted schematically in Fig. 3. Barker's asperity model provides a reasonable gouging initiation velocity and results in gouging damage with shape similar to observed damage. The model requires, however, the existence of a small asperity along the path of sliding contact. Furthermore, the model predicts that the size of gouging damage depends on the size of asperity. In the case of high-velocity guns, the barrel is carefully machined and asperities are removed; yet even though the gouging velocity is substantially higher than that of rocket sleds, the gouging still occurs. In the Gerstle's experimental study (1968) of gouging phenomenon, small beads were welded across the width of the rail and his results demonstrated that small irregularities on the surface of guider (rail) do not necessarily cause gouging.

In this paper, an alternate model (Tachau, 1991) is proposed for explaining the formation of gouges. The development of the model is presented in section 2. The simulation of gouge formation is numerically carried out by applying the CTH strong

shock physics code (McGlaun et al, 1990) in section 3. A discussion of the model and the results from the study is presented in the concluding section--section 4.

2.0 Development of The Model

It is known that rocket sleds are subjected to intense vibration as they travel along their guide rails. It is reasonable to deduce that the vibration of sled shoe (slider) creates a velocity component perpendicular to the direction of travel and this normal velocity component, together with the sliding velocity, result in a very shallow oblique impact between the slider and its guider. The impact produces an intense pressure and heat that cause a softening of the material at and near the contact surfaces. This results in the formation of a thin viscoplastic layer at the contact surface. Indeed, post-test examination of gouges reveals that the material has experienced intense heating and melting.

Abrahamson and Goodier (1961) analytically demonstrated that an anti-symmetric "hump" deformation would precede a normal load (slider) moving along a layer of soft material. A gouge may thus be produced when the hump is overrun by the slider. In fact, the hump may be regarded as the gouge-initiating asperity in Barker's model.

In the proposed gouging model the slider is given a very small velocity component that is perpendicular to the surface of the guider. This normal velocity component may be produced by vibration or aerodynamic loading of the sled structure (Korkegi and Briggs, 1969). These inputs cause an intermittent, but random, contact between the slider and the guider. The shallow oblique impact, together with the resulting high surface temperature and pressure, provide the condition for forming a gouge. The CTH hydrocode was used to numerically simulate gouging conditions and the progression of gouge formation.

2.1 The CTH Code

Numerical simulation of slider/guider interactions were performed using the CTH strong shock physics code. A published description of some of the features of CTH can be found in McGlaun, et al (1990). In this section, we will summarize those features of the code that are relevant to the present work.

2.1.1 General Description of CTH

CTH is a 1-, 2-, and 3-D, multi-material, finite-volume shock physics code that treats large deformation material flow motion with strength. The code uses a logically rectangular Eulerian grid. Thus, the mesh remains fixed during the course of a calculation, while material moves through the mesh. The basic hydrodynamic algorithms consist of two computational steps for each overall calculation cycle. First, the basic Lagrangian conservation equations of mass, momentum, and energy are solved, yielding material deformation and a deformed mesh. Then, this mesh is rezoned back to the original configuration. Second-order algorithms are used to perform both steps, yielding overall second-order accuracy of the code. For the Lagrangian step, the major distinction between CTH and traditional Lagrangian codes is that velocities are cell edge centered, rather than cell corner centered. Otherwise, standard staggered-grid positioning of the computational variables, such as temperature, pressure, stress deviators, and velocities is used. The interested reader should consult McGlaun and Yarrington (1993) for a discussion of this type of computational mesh. Second-order interface tracking techniques are used to track individual materials and their interfaces during the course of calculations. These techniques, and the second-order solution algorithms, considerably reduce the numerical material diffusion that plagued earlier multi-material Eulerian compressible flow codes.

Because of the Eulerian computational mesh, multiple materials are allowed to occupy individual computational cells at given times. The hydrodynamic algorithms required for mixed-material computational cells are summarized in McGlaun, et al (1990).

CTH is an explicit code, with stability-limited time steps computed by a Courant condition which has been supplemented by time step limits controlled by material flow through the computational cells. Artificial viscosity is used to allow computation of material motion with shock waves present. Computational pseudo-stresses, such as anti-keystone viscosities, are not required because of the nature of the mesh.

2.1.2 Material Models in CTH

The fundamental equations of motion in CTH must be supplemented by additional equations which specify the equations of state and the strength behavior of all of the materials in a given problem. The equation of state of a material specifies the relation of the pressure of the material (mean stress) to the internal energy (or temperature) and density. The strength behavior of a material, here called the "constitutive relation" is a specification of the dependence of the stress deviators upon the temperature, strain, and strain-rate of the material (and, more generally, upon the history of these quantities).

CTH allows several different options for modeling the equation of state of a material. These include the ideal gas equation of state, the Mie-Gruneisen equation of state (McQueen, et al, 1970), the ANEOS equation of state (Thompson and Lauson, 1972), and SEAME tabular equations of state (Holian, 1984). In the present calculations, we have elected to use the ANEOS equation of state. This allows us to model, in a thermodynamically consistent way, the melt and vaporization phase transitions in metals that are of importance in high pressure gouging phenomena.

Several different constitutive models are also available in CTH, including elastic-perfectly plastic and several different viscoplastic models. We have used the simple elastic-perfectly plastic model in the present work because details of strain-rates and constitutive history are not important for a gross evaluation of the proposed model. The yield strength in the elastic-perfectly plastic model does degrade as a function of temperature, beginning (as a default) to reduce its value when the temperature of the material is eighty percent of the melt temperature. At melt temperature and above, the yield strength is zero. Volume averaging of yield strengths is used in computational cells having multiple materials to determine a single volume average yield strength.

2.1.3 Sliding Interfaces

CTH is not a multi-phase flow code. A single velocity field is defined for a calculation. This leads to difficulties in accurately modeling sliding interfaces. If a stationary material interacts with a moving material in a cell, both materials in the cell have acquired the same velocity at the conclusion of a time step. This makes sense for penetration or collision of one material by another, but not in the case of pure sliding contact. This treatment then tends to model a "sliding interface" as if the materials were "welded". Because the model of gouging that we are investigating does not involve pure sliding contact, but rather also has an additional component of velocity normal to the interface, this treatment of material interfaces contains elements that are correct.

One additional modification to the usual code treatment of the interaction of sliding bodies has been used. This modification sets shear stresses to zero in cells that include the interface between the slider and the guider in our calculations. The major impact of this algorithm is to eliminate stresses that are produced purely by the "sliding" contact of the two bodies in these calculations. These stresses could produce fictitious

pressures of tens of kilobars in magnitude at an interface with purely tangential motion in CTH calculations, so the impact of this change is quite substantial.

3.0 The Simulated Results

The simulations presented in this paper were executed on a Cray YMP computer at Sandia National Laboratories.

3.1 Equation of State

For the simulations performed in this study, the material for both slider and guider was steel. In the CTH code, the material is modeled as an elasto-plastic material which obeys the von Mises yield surface and the material is thermally softening. The slopes of the shock Hugoniot in the particle-velocity/ shock-velocity plane are used to calibrate the equation of state for the material. The pertinent material parameters used in the calculations are listed in Table 1.

3.2 Mesh Layup

The initial slider-guider configuration is shown in Fig. 4a. Note that the lower right corner of the slider is rounded and has a 0.5 cm radius. The mesh used in the calculation contains 48,000 cells as shown in Fig. 4b. The cells in the central area are 1 mm². The guider material fills the lower half of the mesh ($y = 0$ to 15 cm, $x = 0.5$ to 75 cm), and the slider initially occupies the upper left of the mesh ($y = 15$ to 30 cm, $x = 0.5$ to 25 cm). As the time advances from $t = 0$, the slider moves from left to right into the void portion of the mesh.

3.3 Simulation Results

The slider is given a horizontal velocity of 2 km/sec and a vertical velocity of 0.1 km/sec. The calculated interface displacement, temperature, and pressure distribution at $t = 40 \mu\text{sec}$ and $124 \mu\text{sec}$ are plotted in Figs. 5a, 5b; 6a, 6b; and 7a, 7b; respectively. The following observations are made:

1. It is clear from Figs. 5a and 5b that the slider-guider interface undergoes a severe localized deformation. At $t = 40 \mu\text{sec}$, the interface is deformed a few millimeters behind the leading edge of the slider. As the time advances, the deformation increases in magnitude, but stays centered around the initiation point just after the slider's leading edge. The center of the deformed area moves forward with a velocity approximately one-half of the slider's velocity. The damage area continues to grow in size and in depth. At $t = 124 \mu\text{sec}$, a gouge similar to that sketched in Fig. 2 is formed.
2. The temperature contours near the interface are shown in Fig. 6a and 6b. The contour values are: $A = 1000$, $B = 1700$, and $C = 1800 \text{ deg-K}$. It is seen that the heating occurs only in a very shallow zone near the interface. Because the temperature gradient is very steep, the plots are amplified to provide a better view of the contours. It is clear that the impact-produced temperature rapidly heats the surface material to its melting temperature.

It is interesting to note that the ejecta's temperature (shown in Fig. 6b.) remains at or near the melting temperature of the material. This confirms the experimental observation that molten ejecta is a by-product of gouging. It is also interesting to observe the correspondence between the local "hot spot" in Fig. 6a and the initial interface deformation shown in Fig. 5a. The gouge begins to form only

when the material is heated to near its melting temperature and the material becomes viscoplastic.

3. The pressure contours are shown in Fig. 7a and 7b. The contour values are: $C = 400$, $D = 800$, $E = 2,500$, and $F = 5,000$ MPa. It is seen that the oblique impact produces a growing high-pressure "core" at the contact surface as shown by the shaded area in Figs. 6a and 6b. This growing high-pressure core is a necessary condition for the gouge to form and to grow. It has been shown by Tachau (1991), in a parameter study of the problem, that if the vertical velocity component of the slider is not sufficiently high, the pressure core will not grow and a gouge will not form; despite the fact that the slider has a high horizontal velocity and a high interface temperature is generated by the sliding contact. In this case, superficial surface damage is caused by the sliding friction, but not by the gouging.

4.0 Discussion and Conclusion

The results from this study clearly demonstrate that the gouging is produced by a very shallow oblique impact between the slider and the guider. The impact causes a sharp increase of temperature that produces a thin soft layer between the contact surfaces. This layer of soft material deforms anti-symmetrically under a moving load. When the hump of the soft layer is displaced by the slider, a gouge is formed on the contact surface.

Experimental evidence has confirmed that gouging damage occurs on the contact surface of both the slider and the guider. Metallographic analysis of the materials on and near the gouged surfaces has also confirmed that the material is indeed melted by the intense heating (Barker, et al, 1987) produced by the impact. The model presented in this study offers a logical explanation of the phenomenon.

By using an asperity on the surface of the guider, Barker et al (1987, 1988) were able to demonstrate the formation of a gouge. With some reflection, it becomes clear that when a spherical asperity is impacted by a slider with a sloped impact surface, the deformation of the asperity imparts a vertical momentum or impulse on the surface of the guider. This vertical impulse is the necessary condition for the formation of a gouge in Barker's model. In the model presented in this paper, the source of the vertical impulse may be a slight misalignment between the sled and the rail, by vibration of the sled itself, or by aerodynamic loading on the sled structure. When the magnitude of the resultant impulse vector (despite its shallowness) is sufficiently large, and when the contact surfaces are sufficiently softened by the heating, the removal of the anti-symmetric deformation (hump) on the interface by the slider produces a gouge. Since the above mentioned vertical impulse is difficult to quantify and to predict, it is not surprising that gouging appears to be a random event in the rocket sled testing.

The presence of a high-pressure growing core, as a necessary condition for gouging, is an important discovery in Barker's study. This suggests that the onset of gouging can be avoided, or shifted to a higher velocity threshold, with a shoe designed to prevent or to retard the growth of the high-pressure core. Based on this observation, Barker (1986) provided the notional concept of a laminated composite rocket sled shoe design. A sled shoe, based on this concept, was developed and tested by Kampfe and Tachau at Sandia's 10,000-Foot Rocket Sled Test Facility. The shoe has been proven to be successful in mitigating the formation of gouges in several high-velocity rocket sled tests.

In high-velocity guns, the barrel is accurately machined and aligned and the projectile is carefully balanced. The magnitude of impulse produced by any projectile unbalance or barrel misalignment is small in comparison with that occurring in the rocket

sled tests. As a result, the threshold gouging velocity for the high-speed guns is substantially higher than that experienced in the rocket sled testing.

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Table 1:
Material Parameters Used in Numerical Simulations

Yield pressure	= 700 MPa
Poisson's ratio	= 0.3
Reference density, ρ_0	= 7.85 gm/cc
Reference temperature, T_0	= 298 K
Reference bulk modulus, B_0	= 1.45×10^{12} dynes/cm ²
Separation energy ($T = 0$), E_s	= 8.20×10^{10} ergs/gm
Melt temperature, T_m	= 1809 K
Heat of fusion (melt transition), H_f	= 2.471×10^9 ergs/gm

Figure 1: Photograph of a Rocket Sled Rail Gouge
(Approximately one-half actual size)

Figure 2: Sketch of a Typical Rail Gouge

Figure 3: Formation of a Gouge -- Barker's Model

Figure 4a: Initial Slider-Guider Configuration and Dimensions

Figure 4b: The Eulerian Mesh Used for the Simulation Study

Figure 5a: Slider-Guider Interface at $t = 40 \mu\text{sec}$

Figure 5b: Slider-Guider Interface at $t = 124\mu\text{sec}$

Figure 6a: Temperature Contours at $t = 40\mu\text{sec}$

Figure 6b: Temperature Contours at $t = 124\mu\text{sec}$

Figure 7a: Pressure Contours at $t = 40\mu\text{sec}$

Figure 7b: Pressure Contours at $t = 124\mu\text{sec}$

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