Available online at www.sciencedirect.com

ScienceDirect

Defence Technology 12 (2016) 90–95

www.elsevier.com/locate/dt

3D numerical simulation and analysis of railgun gouging mechanism

Jin-guo WU *, Bo TANG, Qing-hua LIN, Hai-yuan LI, Bao-ming LI

National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu, China

Received 15 September 2015; revised 21 December 2015; accepted 22 December 2015

Available online 19 January 2016

Abstract

A gouging phenomenon with a hypervelocity sliding electrical contact in railgun not only shortens the rail lifetime but also affects the interior ballistic performance. In this paper, a 3-D numerical model was introduced to simulate and analyze the generation mechanism and evolution of the rail gouging phenomenon. The results show that a rail surface bulge is an important factor to induce gouging. High density and high pressure material flow on the contact surface, obliquely extruded into the rail when accelerating the armature to a high velocity, can produce gouging. Both controlling the bulge size to a certain range and selecting suitable materials for rail surface coating will suppress the formation of gouging. The numerical simulation had a good agreement with experiments, which validated the computing model and methodology are reliable.

Keywords: Impact dynamics; Gouging; Finite element simulation; Rail damage; Railgun

1. Introduction

The electromagnetic railgun is a kinetic energy weapon utilizing an electromagnetic force produced by a high power pulse current to accelerate a projectile to a high speed. It has wide applications in military and civil fields [1–3]. How to extend the lifetime of the launcher is a key technology of a railgun. It depends on the solutions of arc ablation [4,5] and gouging problems. Gouging is a material damage phenomenon appeared in hypervelocity sliding contact, which has been reported in rocket sled, light-gas gun and railguns [6–8]. Gouging in a railgun will result in the following main hazards: reducing the energy utilization, shortening the rail's lifetime and affecting the accuracy of projectile. The typical teardrop shaped gouging morphology observed during post-shot inspections of rails is illustrated in Fig. 1. The depth varied along the length of the gouge and was shallowest close to the point of initiation. In addition, armature deposits were observed at the raised gouge lip. Watt et al. [9] found that both galling and gouge craters initiated from existing microscopic defects and the microscopic defects had no measurable effects on the threshold velocity for either galling or gouging damage. Barker et al. [10] and Bourell et al. [11] conducted numerical simulations for the gouging mechanism utilizing CTH and EPIC codes respectively, but both of them were 2D models.

This paper is intended to carefully describe the formation of gouging and better understand the gouging mechanism through 3D thermal mechanical coupling simulations. And parameter studies were presented in the simulations. Some factors affecting the gouging, such as the bulge size and materials, were discussed.

2. Computing model and parameters for railgun gouging

2.1. Computing model

Many researchers have explored the mechanism of gouging [12–16]. A prevalent hypothesis is that rail surface defects and the dynamic response of the rail, often microscopic in size, are the importance causes of rail gouging. The impact between the armature and the local asperities or rail bulge leads to a local pressure far exceeding the yield strengths of the contact materials, and hence a micro-crater is formed.

In the paper, a 3D model of a rail bulge impacted by a C shaped armature (Fig. 2) was established for the simulation with the finite element method. The rail was divided with 80,809 elements and the armature was divided with 30,380 elements. For more accurate calculation, dense meshes were constructed around the rail bulge (Fig. 2a). The specific armature sizes are illustrated in Fig. 2b, the same as the armature used in the experiment. Due to the symmetry of physical structure, along the symmetrical plane only half of the armature and one rail were adopted in the model. A displacement constraint in the y direction was applied on the symmetrical plane of the armature. And insulating and supporting materials were

Peer review under responsibility of China Ordnance Society.

* Corresponding author. Tel.: +8615195985767.
E-mail address: wujg8848@163.com (J.G. WU).

http://dx.doi.org/10.1016/j.dt.2015.12.006
2214-9147/

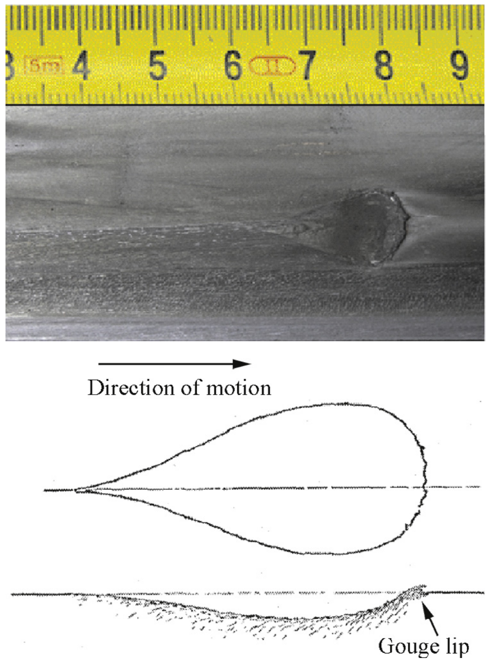

Fig. 1. Typical teardrop shaped gouge crater in railgun experiment.

omitted in the model, instead displacement constraints were applied on the sides of the armature. According to some studies [17,18] on the dynamic response of the rail, a bulge size of 1 mm was supposed on the rail in the simplified model, which would induce the impact with the armature.

2.2. Material model and parameters

The Johnson-Cook model, i.e., the strain and temperature sensitive plasticity material model, was used for the computation, which is described as follows:

$$\sigma_y = [A + B(\bar{\varepsilon}^{\mathrm{p}})^n](1 + c\ln\dot{\varepsilon}^*)(1 - T^{*m}) \tag{1}$$

where A, B, n, c, m are input constants; $\bar{\varepsilon}^{\mathrm{p}}$ is the effective plastic strain; $\dot{\varepsilon}^*$ is the normalized effective plastic strain rate; $T^* = \frac{T - T_{\mathrm{room}}}{T_{\mathrm{melt}} - T_{\mathrm{room}}}$, T_{melt} is the melting temperature of materials and T_{room} is the environment temperature.

The strain at fracture is expressed as

$$\varepsilon^{\mathrm{f}} = (D_1 + D_2 \mathrm{e}^{D_3\sigma^*})(1 + D_4 \ln\dot{\varepsilon}^*)(1 + D_5 T^*) \tag{2}$$

where σ^* is the ratio of pressure divided by the effective stress: $\sigma^* = \frac{p}{\sigma_{\mathrm{eff}}}$; $D_1 - D_5$ are failure parameters. Fracture occurs when the damage parameter

$$D = \sum \frac{\Delta\bar{\varepsilon}^{\mathrm{p}}}{\varepsilon^{\mathrm{f}}} \tag{3}$$

reaches the value of 1.

The Mie–Grüneisen equation of state was adopted to describe the thermodynamic behavior of materials at high pressure. The pressure for compressed materials is defined as

$$p = \frac{\rho_0 C^2 \mu\left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (s_1 - 1)\mu - s_2\frac{\mu^2}{\mu + 1} - s_3\frac{\mu^3}{(\mu + 1)^2}\right]^2} + e(\gamma_0 + a\mu) \tag{4}$$

and for expanded materials, is

$$p = \rho_0 C^2 \mu + e_0(\gamma_0 + a\mu) \tag{5}$$

where C is the intercept of the $v_{\mathrm{s}} - v_{\mathrm{p}}$ curve (v_{s} is the shock velocity and v_{p} is the particle velocity); s_1, s_2, s_3 are unitless coefficients of the slope of the $v_{\mathrm{s}} - v_{\mathrm{p}}$ curve; e_0 is the initial

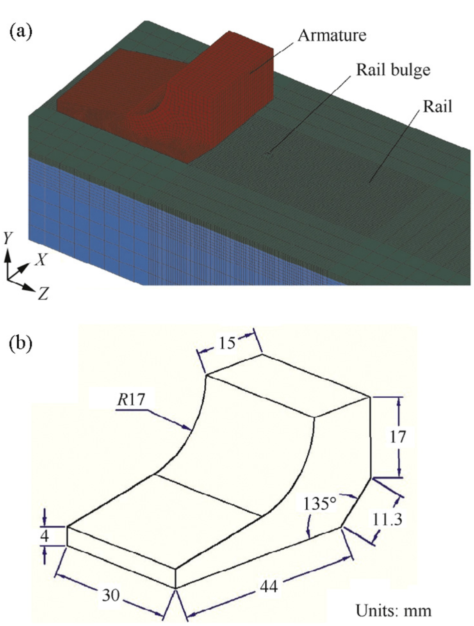

Fig. 2. 3D computing model for railgun gouging.

Table 1
Material parameters of armature and rail.

Parameters	7075 Al	OFHC copper
Density/(kg·m^{-3})	2810	8960
E/GPa	71	124
V	0.33	0.34
Specific heat capacity/(J·kg^{-1}·K^{-1})	960	383
T_{melt} /K	933	1356
A/MPa	369	90
B/MPa	684	292
N	0.73	0.31
c	0.0083	0.025
m	1.7	1.09
D_1	0.13	0.54
D_2	0.13	4.0
D_3	−1.5	2.0
D_4	0.011	0.014
D_5	0	1.12
C/(m·s^{-1})	5350	3940
s_1	1.34	1.49
s_2	0	0
s_3	0	0
γ_0	2.0	2.0