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Effect of Pre-Existing Defects on Fracture of Electromagnetically Accelerated Projectiles: Comparison of Simulations and Experiments

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Abstract

Induction coil gun uses electromagnetic forces to accelerate metallic tubular projectiles for impact studies. It consists of a helical coil and a cylindrical projectile placed coaxially with the coil. Electromagnetic flux linkage between the coil and the projectile sets up axial and radial forces on the projectile. The axial force accelerates the projectile out of the coil, while the radial force leads to *pinching*. In certain experiments, projectiles are non-uniformly pinched and undergo plastic buckling. This is manifested in longitudinal cracks that degrade system efficiency. These cracks cannot be handled in a R-Z axisymmetric model. Hence we have developed a composite model consisting of MHD R-Z (axisymmetric) and 2D-Hydrodynamic X-Y (plane geometry) models to study deformation and longitudinal cracking. Our study predicts that an initial perturbation in projectile thickness along the θ direction can grow and lead to localization of plastic strains causing longitudinal cracking.

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Keywords: projectile fracture, electromagnetic pinching, plastic buckling, strain localization

1. Introduction

Induction coil guns have been used to accelerate metallic projectiles to velocities of a few hundred meter/s [1, 2]. Figure 1 shows a schematic of one design of an induction coil gun. The discharge of a charged capacitor through the coil sets up time-varying flux linkage with the projectile. This induces time-varying eddy currents that vary through the projectile length and also as a function of depth through the projectile thickness. The interaction of these eddy currents with the magnetic field produces axial and radial electromagnetic forces. The axial force tends to accelerate the projectile out of the coil, while the radial force leads to pinching. The eddy currents lead to non-uniform joule heating of the projectile, in turn affecting the spatio-temporal variation of its electrical resistivity.

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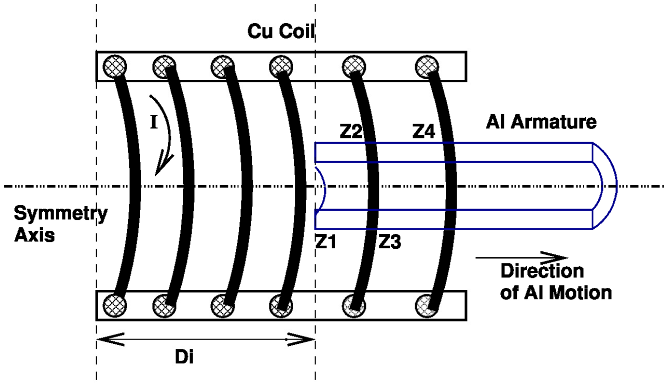

Figure1. Schematic of coil gun in R-Z axisymmetric plane

Due to heating the mechanical strength of the projectile is degraded leading to heavy radial pinching. Pinching affects the efficiency of the system in two ways. Firstly, it reduces the magnetic flux linkage between the projectile and the coil. Secondly, heavy pinching has been found, in our experiments, to produce longitudinal cracks on the projectile. Azimuthal currents are interrupted at crack locations, which reduces the net axial acceleration of the projectile. Thus it is necessary to understand the conditions under which cracking occurs, and to suggest methods to eliminate cracking. This is best done through simulations. We report in this paper our computational study on the radial pinch/deformation of the projectile and associated longitudinal crack/buckling.

2. Computational Model

A complete three-dimensional magnetohydrodynamics (MHD) simulation being infeasible, we have developed a composite model, consisting of a 2D R-Z model (cylindrical symmetry), followed by a 2D X-Y model (plane geometry). Our axisymmetric two-dimensional (2D) MHD model [3] has already been validated against in-house coil gun experiments. The MHD model is self-consistently coupled to a circuit solver that evolves coil current and capacitor discharge voltage as functions of time. Electromagnetic coupling and forces are calculated in 2D axisymmetric R-Z plane. Time varying electromagnetic forces and joule heating at various radial and axial "computational cells" on the projectile are recorded from this 2D-MHD model. These are then used in the 2D X-Y plane hydrodynamic model.

2.1 Axisymmetric (R-Z) Cylindrical 2D MHD Model

A cross-sectional (R-Z cylindrical plane) view of the coil gun is shown in figure 1. Cylindrical symmetry makes it sufficient to model only the portion above the symmetry axis. Current flows through the coil which are assumed to be set of circular rings whose cross section is shown in the figure 1. The projectile (marked as Al armature in figure 1) is placed coaxial with the coil. For a coil gun system, the electromagnetic force on the projectile carrying eddy currents has both axial and radial components. The instantaneous force on the projectile and therefore its instantaneous acceleration can be calculated by knowing the current density distribution through the projectile and the magnetic field throughout the domain. These, in turn, require the calculation of instantaneous coil current, which comes from a circuit solver coupled to the MHD solver. Details of the circuit solver are not included here since the focus of this paper is on the mechanical fracture of the projectile.

The code uses appropriate equations of state for the Aluminium (Al) projectile and the copper (Cu) coil. For the problem reported here we used Johnson-Cook (JC) [4] model for dynamic strength calculations. It takes care of the dynamic mechanical properties due to strain hardening, thermal softening and high strain-rate deformation.

Our 2D-MHD R-Z code gives the evolution of radial inward deformation all along the length of the projectile. The extent of radial pinch varies as we move along the axial direction. Since 2D computational domain is computationally discretized in both axial and radial directions, we know time varying radial forces at each of these discretized computational grids. For our study, we have chosen four axial locations marked as Z1, Z2, Z3 and Z4 in Figure 1. For these four locations, the time varying electromagnetic forces are recorded as functions of radial