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SMALL CALIBER MODELING FROM DESIGN TO MANUFACTURE TO LAUNCH

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The US Army transition to environmentally friendly green ammunition has necessitated the development of modeling techniques for small caliber ammunition in order to evaluate alternative materials. This work is focused on the development of a numeric modeling capability to facilitate design, manufacture and launch of small caliber projectiles. Manufacturing modeling has been performed using ABAQUS. Load profiles and stress histories were predicted from the numerical models for different critical manufacturing stations [1]. Predicted loads and experimental load data is in excellent agreement and shows the ability to predict the manufacturing behavior of the projectiles. The interaction between small caliber projectiles and rifled barrels is evaluated through explicit finite element analysis (FEA) simulations conducted with LS-Dyna. Results show that the explicit dynamic simulations can predict the in-bore behavior, particularly how small caliber projectiles engrave and obturate. The results of the simulation and the resulting projectile deformation patterns are compared to the rifling engagement patterns visible on projectiles that have been soft recovered. The simulation results of the M855 and the experimental validation data are presented. The modeling methodology has created the capability to predict the effect of both material and geometry changes on the manufacturing and in-bore behavior of small caliber ammunition.

INTRODUCTION

Small caliber projectiles, such as the M855 [2] ball round, are some of the simplest munitions in the Army inventory. The M855 projectile is comprised of three components: a lead-antimony slug, a steel core penetrator and a copper jacket. This ammunition is used in service and training for the M16A2/A3/A4, the M4, and the

M249 weapon systems. The US Army has a program to investigate alternative “green” materials to replace the lead slug and thereby reduce the risk to the environment [3]. These materials can either be a drop-in replacement for the current lead-antimony [Pb-Sb] slug material, or they can vary widely if the design of the projectile is changed. Analyses are required for predicting both the manufacturing and the in-bore behavior of these new materials.

During projectile manufacturing a metal cup is subjected to numerous draw and punch operations to form the metal into shape. Internal components are inserted into the drawn shape and consolidated under loads. These operations introduce stresses into both the projectile and the tooling that are material and geometry dependant. Manufacturing models provide the ability to obtain an in-depth understanding of the material behavior during manufacturing as well as the residual stresses within the completed part.

Due to the size of the M855 projectile, the interaction between the projectile and the weapon system cannot be readily measured during launch using traditional techniques such as x-ray and shadowgraph as they do not provide the resolution required to examine the physical state of the projectile surface. Numerical simulations provide an indirect means of examining the in-bore motion and interaction of the weapon and projectile. Explicit dynamic finite element analysis (FEA) simulation codes can be applied to evaluate the interaction between the projectile and a rifled barrel. The resulting launched projectile contains the deformation patterns due to the engagement with the rifling profile of the barrel. There has been research into the dynamic interactions between a small caliber projectile and the barrel [4]; however, these efforts have been limited in scope and the level of detail investigated. A high level of model mesh refinement is required to accurately evaluate the interactions between the projectile and the barrel.

MANUFACTURE MODELING

Structural simulation of the complete bullet assembly process was undertaken to better understand material behavior, stresses in the projectile parts as well as tooling. Understanding the physics of the process can lead to improved process settings. All necessary stations starting from drawing the jacket from the annealed gilding metal cup to final bullet were modeled. Each manufacturing station produces residual stresses in the parts. In order to properly evaluate the manufacturing behavior it is important to track the stress history due to the manufacturing steps. The process begins with an annealed gilding metal cup. To model the manufacturing of this metal cup, the ABAQUS software has been applied. Figure 1 shows four of the stations for drawing the jacket from a cup.

Utilizing ABAQUS both static and explicit dynamic analyses of all four stations has been performed. Results of both these analysis agreed well. Several bullet assembly machines [BAM] have been instrumented to obtain load versus time data for each station. Force-time data from the simulations agreed well with the measured load data. Jackets at various stages of drawing operations were cross-sectioned to measure jacket profiles to compare with the simulated results. Results of these simulations matched well with the measured data. The right side of Figure 1 shows the finite element model of the jacket after the first draw overlaid on the actual jacket cross section. This overlaid picture shows that the model has the ability to predict the deformations caused by the manufacturing process.

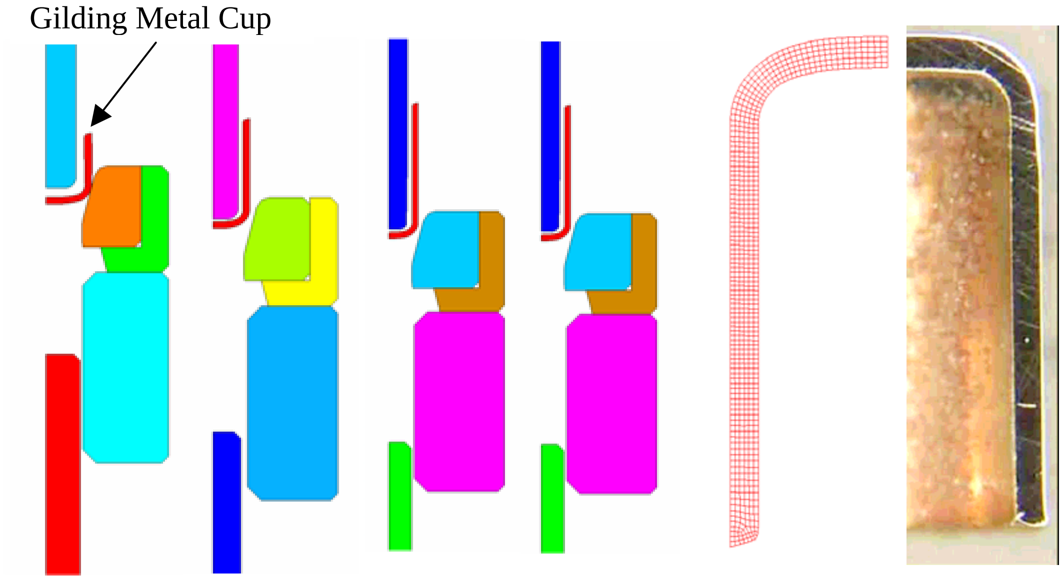

Figure 1 Models of the manufacturing stations for jacket drawing and an overlay of actual jacket after first draw over the predicted jacket profile. The gilding metal cup is being drawn longer

After the jacket drawing operation is completed in the analysis, the drawn jacket goes to several pointing operations for the formation of the full metal jacket and then to the rest of the assembly. Figure 2, from left to right, shows slug consolidation station, base coning and boattailing models. The model clearly shows how the material flows and stresses are created and relieved during the manufacturing process. Various slug materials have been modeled to determine the force required to properly consolidate the slug. Consolidation is necessary to ensure proper rifling engagement during launch [1]. Results of the analyses showed that for each material there is a minimum slug consolidation load that needs to be applied to assure that the slug is consolidated completely. As a result of the analysis, tooling changes were implemented.

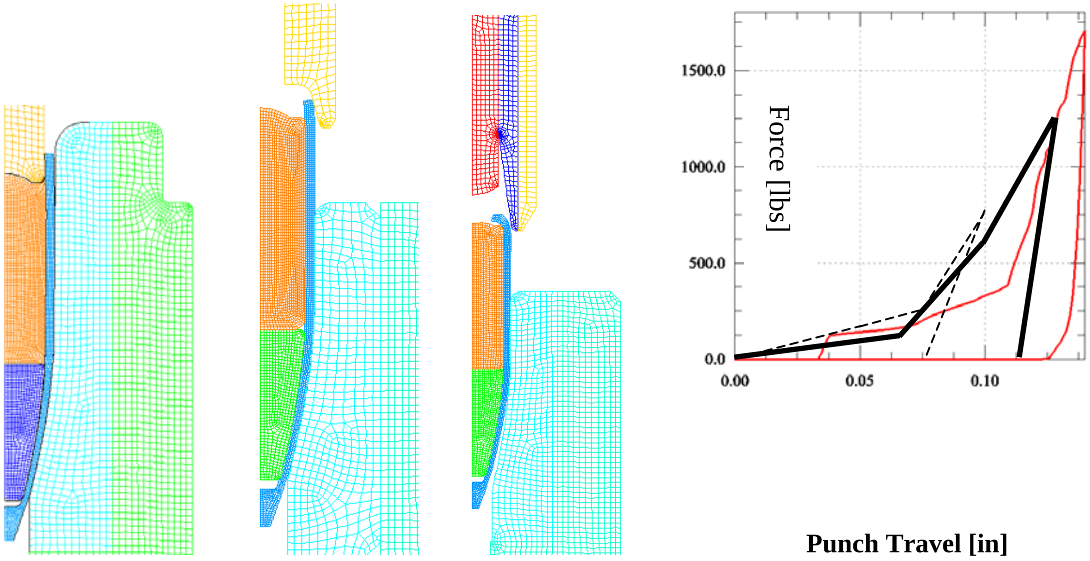

Figure 2 Slug consolidation station, base coning and boattailing models (Left to right). The plot is of the force versus travel for slug consolidation station (dashed), base coning (bold) and boattailing (thin).

The predicted residual von Mises stresses in the bullet after variety of bullet assembly operations are shown in Figure 3. The figure shows that there are significant stresses remaining in the bullet that may affect the in-bore behavior of the bullet during launch. The highest residual stresses are in the boattail and the nose regions of the bullet.

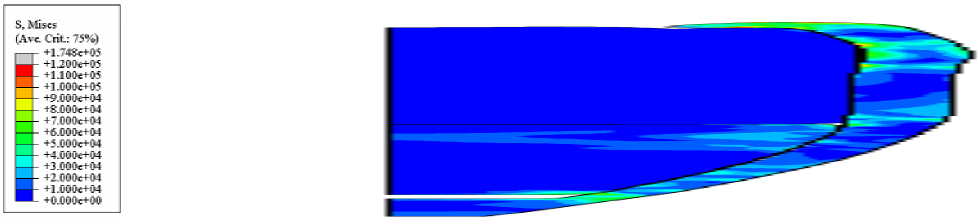

Figure 3 Residual von Mises stress in the bullet due to manufacturing.

Structural modeling of the bullet manufacturing process shows the ability to predict the manufacturing behavior of the projectiles. The level of understating obtained from the modeling may not be possible any other way. The correlated model helps setup the range of optimum manufacturing parameters.

IN-BORE MODELING

During launch of a small caliber projectile, several events happen in order to obturate and spin the projectile. The ability for the projectile to perform these tasks is a function of projectile and barrel design and the projectile materials. Previous research on the in-bore behavior of lead-antimony and tungsten-nylon projectile slugs in a smooth bored barrel has shown that there are differences in how the projectile obturates. Previous research utilizing smooth bores simulations have discerned several key features of the projectiles at peak acceleration [3]. The first key feature is that the jacket in the rear boattail portion of the projectile is clamping down on the back of the slug. The second key feature is that the jacket acceleration is greater than the slug/core acceleration thus creating an internal gas seal. Thirdly, the cylindrical section of the projectile provides the projectile/bore gas seal (e.g. obturation). Both the front section and rear section of the cylindrical portion of the slug are expanding in the radial direction forcing the jacket into the bore of the gun barrel. In a full 3D simulation, this radial expansion provides the pressure necessary to cause the jacket to flow around the rifling as the projectile engages the lands in the gun (not modeled in this simulation).

Full 3D rifled finite element simulation was performed using LS-Dyna. The geometry for both the projectile [2] and the weapon [5] were obtained from their respective technical drawing packages. The barrel was assumed to be an ideal barrel with perfect symmetry and centerline. Axial boundary conditions were applied to the base of the barrel extension to prevent motion of the barrel. The base pressure-time curve for the M855 was obtained from the ballistic code IBHVG2. Contact was used between the slug-core-jacket and the jacket-barrel. All of the components within the projectile were kinematically constrained by contact surfaces. The model was built with the x-axis aligned with the barrel. The material properties for the components in the model were obtained from experimental data. The model parameters were set such that the interaction between the projectile and the barrel would create plastic deformation in the jacket but not erode away the elements. This approach was chosen for it allowed the evaluation of only material deformation due to the interaction with the ballistic pressure and the barrel.

Figure 4 shows the FEA model. The figure shows the outer diameter profile of the barrel. Included in the figure is a M855 projectile that has been launched through the barrel. The projectile shows visible plastic deformation on the outside of the jacket. An enlarged view of the projectile in Figure 4 provides closer view of the plastic strain (permanent deformation) pattern on the outside of the projectile. The figure was taken at a time after the projectile has left the barrel and is translating freely. The figure clearly shows the rifling profile produced on the projectile jacket due to the interaction with the barrel. The resulting plastic deformation on the projectile due to interactions with the lands and grooves are dominant in the figure.

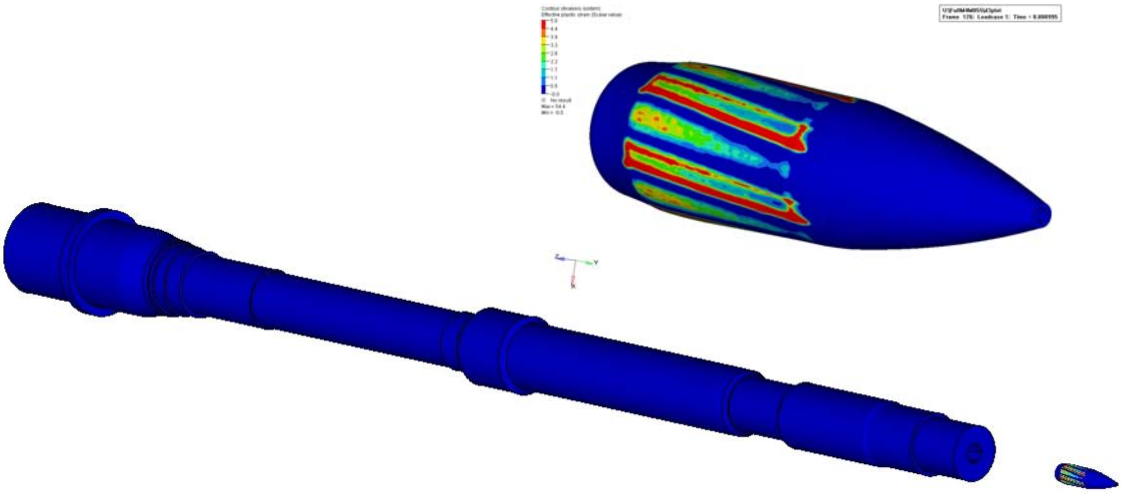

Figure 4 Picture of the FEA model showing the outer diameter of the barrel and a launched projectile.

The predicted deformation patterns show the effect of the radial expansion. Under the applied ballistic pressure the slug will deform inelastically and try to expand outward. This attempted expansion will drive the jacket toward the lands and the grooves. Figure 4 shows the manifestation of this attempted expansion by a greater amount of deformation near the boattail in both the land and the groove. This deformation begins to decrease moving forward toward the projectile ogive. The nature of the radial expansion between the rifled and the smooth barrel FEA models are qualitatively the same.

DISCUSSION

The predicted deformation pattern of the M855 was compared to the patterns on soft recovered rounds. Digital photographs where taken of the recovered projectiles to allow both for inspection of the barrel-projectile interaction and to create a medium from which the numerical simulation results could be compared. Photographs where taken at 9.5 times magnification using a Diagnostic Instruments Inc. CCD camera attached to a WILD TYP 355110 microscope. The cylindrical surface of the projectiles were captured as six planar pictures. The digital pictures of the six sections were then composited as one image. This partitioned approach resulted in the three dimensional exterior of the projectile being mapped down into one two-dimensional image. Figure 5 shows a planar picture of a soft recovered round. The regions inside the dashed –line boundaries are the wear patterns due to interaction with the rifling groove. The barrel that the projectile in Figure 5 was fired appears to have had a worn land. This worn land is Land#3. The worn land resulted in the projectile appearing to "slide" before becoming engaged. There is a sliding wear pattern that begins in the groove then transitions into the land. This transition pattern is apparent in the third land pattern in Figure 5 as a forty five degree line across the base of the groove into the land.

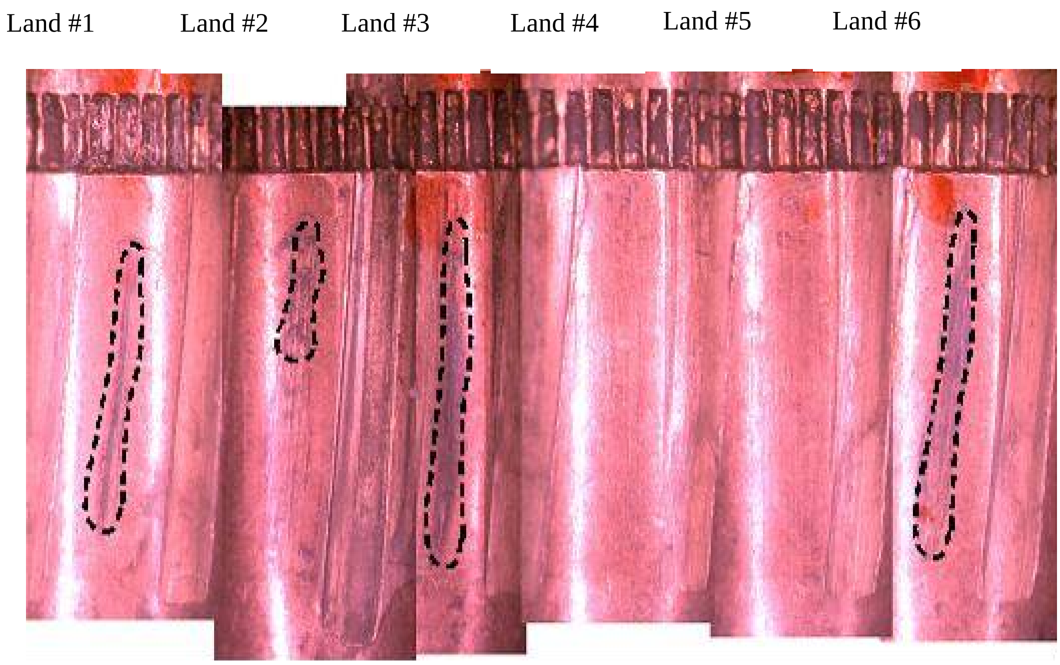

Figure 5 360° degree picture of recovered projectile #3.

Comparisons between the soft recovered and the predicted behavior of the projectile are quite good. The predicted projectile patterns can be compared to the patterns on soft recovered projectiles. The pattern produced by the interaction with the lands is identical with the exception of the worn land. The wear patterns in the groove between the model prediction and the soft recovered projectile are in very good agreement. Wear on the outer diameter of the projectile due to the groove begins near the boattail and continues toward the cannelure. The model predictions shows wear patterns (plastic deformation) due to an interaction with every groove. The difference between the model prediction and the soft recovered round is that the barrel in the model is ideal and perfectly symmetric. The worn land in the experimental barrel clearly shows that the experimental barrel is not an ideal barrel.

The wear patterns on the outer diameter of the projectile are the manifestation of the behavior of the internal components and the jacket due to the applied ballistic pressure. However these results do not take into account the residual stresses from manufacturing. The manufacturing models predicted the highest residual stresses in the boattail and the nose regions of the bullet. It is unlikely that the residual stresses in the nose region will affect the in-bore behavior but that may not be the case of the residual stresses in the boattail. To refine the in-bore predictions the residual stresses due to the manufacturing process should be incorporated so that an accurate response of the projectile can be predicted.

CONCLUSIONS

This modeling demonstrates the ability to predict the manufacturing and in-bore behavior of small caliber ammunition. The predicted loads and experimental manufacturing load data are in excellent agreement and show the ability to predict the manufacturing behavior of the projectiles. The interaction between small caliber projectiles and rifled barrels was evaluated and the resulting predicted deformation of the projectile was in good agreement the wear patterns on soft recovered projectiles. Together these modeling capabilities allow for complete analyses on the effect of both material and geometry changes on the optimized manufacturing parameters and the in-bore behavior of small caliber projectiles. These tools can be applied to evaluate future small caliber ammunition materials and designs.

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