

Drawbead Restraining Force Modeling: Nonlinear Friction

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ABSTRACT

A detailed investigation of influence of friction on drawbead restraining force modeling is presented in this paper. It is motivated by the need to accurately correlate line bead strengths, which are usually the output of an optimized draw development for controlling materials flow and achieving desired formability, and the physical drawbead geometries required for die face engineering. A plane-strain drawbead model with linear Coulomb friction is first established and the restraining forces corresponding to a range of bead penetration depths are obtained. The comparison of the simulation results with experimental data indicates that, while a larger Coefficient of Friction (COF) has better correlation for smaller bead penetrations and smaller COF does better for deeper bead penetrations, no single COF matches satisfactorily for overall range of bead penetration depths. Nonlinear friction models are subsequently proposed where the friction coefficient is dependent on the contact pressure, justified by a comprehensive review of theoretical and experimental evidences. Their applications to the drawbead modeling yield improved correlations for the restraining forces. The paper focuses on the investigation of the need for such nonlinear friction models, and other possible explanations behind the discrepancy between the test and the simulation are discussed, notably with the emphasis on the influence of materials models as a future study area.

INTRODUCTION

Drawbead design is an integral part of draw development process in die face engineering. By manipulating drawbeads' physical geometries such as their width, height and the radii, die engineers are able to effectively control the restraining forces provided by the drawbeads and therefore optimize materials flow in order to achieve desired formability. The drawbead optimization process is mostly conducted through computer simulations thanks to tremendous advances in stamping modeling over the past decade, where the physical drawbeads are usually replaced by so-called line beads or analytical beads with associated restraining strengths [1-3].

The use of line bead models in stamping simulations as opposed to that of detailed physical beads offers primarily two major advantages: computational efficiency and engineering simplicity. The dimensions of drawbeads are much smaller and detailed compared with the overall geometries of a draw die, and the accurate modeling of the physical geometry of a drawbead requires a huge number of finite elements in order to capture its details, at a tremendous expense of computational resources. Furthermore, the purpose of the drawbeads is to provide appropriate restraining forces to control metal flow, and their detailed design can be reasonably separated from the rest of draw development process after the required restraining forces are determined. It is for this reason that analytical line beads were developed since the early days of stamping simulation. They have been widely used in practical stamping simulations, especially during early

forming feasibility and process optimization stages. The appropriate physical bead geometries are then added to the die faces based on the required restraining forces. Recent advancement in computational power such as the Massive Parallel Processing (MPP) technology, coupled with the robustness of stamping software taking advantage of MPP capabilities, enables CAE engineers to simulate the complete die face with physical drawbeads. This is usually conducted either as a validation of the final draw design or for springback predictions where the modeling of material flow through drawbeads is expected to significantly alter simulation results [4].

It is therefore imperative to establish the corresponding relationship between a specified physical drawbead and the restraining force it provides for a given material. The relationship could be expressed as a look-up table, an algorithm, or a piece of software which allows stamping engineers to select correct drawbead geometry for the required restraining force as derived from forming simulations. Such a relationship can be obtained empirically or through validated numerical simulations. Given the complexities of drawbead geometries and the range of materials used for stamping, however, it becomes clear that an exhaustive testing of all possible combinations would be prohibitively expensive and time-consuming. A more advantageous approach would be to develop predictive simulation models aided by correlation with selectively conducted laboratory tests.

The restraining force generated by a drawbead is due to two mechanisms: the deformation force from bending as the metal flows through the drawbead, and the friction force which comes from the rubbing of the sheet metal against the drawbead surfaces [5]. The accurate modeling of the bending deformation requires fundamental understanding and characterization of the elastoplastic behavior of sheet metals under large strain cyclic loading. This includes the aspects of both the yield surface and its evolution during work hardening. It is currently well accepted that Hill's anisotropic plasticity [6-7] models are a good characterization for most of steels and a series of non-quadratic yield models developed by Barlat and others provide a better alternative for aluminum sheet alloys [8-9]. However, recent research advancement [10-11] suggests that the currently widely used isotropic hardening models might not be adequate for predicting sheet metals undergoing large-strain cyclic loading. Being pulled through a drawbead exemplifies such deformations.

On the other hand, the classic linear Coulomb friction model has been the choice of majority of simulations for sheet metal forming due to its simplicity and the ease of implementation. The frictional coefficient is assumed to be a constant value for any given pair of contact

surfaces and the lubricant. Various experimental techniques exist to measure its value, notably the Twist-Compression test, the pull-through strip test, the Drawbead Simulator test and other test methods [12-17]. However experimental and theoretical investigations revealed that the frictional coefficient often depends on a variety of conditions such as sliding velocity, sliding displacement and contact pressure [18-22]. Consequently forming simulation researchers and engineers are sometimes forced to select a coefficient value in correlation with measurement data from forming tryout out, making it more or less a "fudge" factor.

The influence of constitutive models on the accuracy of drawbead force predictions will be the subject of a separate study. The focus of this paper is placed on the understanding of influence of friction on drawbead restraining force modeling. A plane-strain drawbead model with linear Coulomb friction is first established and the restraining forces corresponding to a range of bead penetration depths are obtained. The comparison of the simulation results with experimental data indicates that, while a larger Coefficient of Friction (COF) has better correlation for smaller bead penetrations and smaller COF does better for deeper bead penetrations, no single COF matches satisfactorily for overall range of bead penetration depths. Nonlinear friction models are subsequently proposed where the friction coefficient is dependent on the contact pressure. Their applications to the drawbead modeling yield improved correlations for the restraining forces. The paper concludes with a discussion of the need for future studies.

DRAWBEAD MODEL

A series of carefully calibrated drawbead tests were conducted as part of the "Enhanced Forming Limit Diagrams" project ([23, 24]) under the Auto/Steel Partnership (A/SP), a collaborative research between US automotive companies and steel companies with sponsorship from the Department of Energy of United States Government. Of particular interests to our study are the restraining forces and associated data obtained by pulling a strip of steels through a drawbead for progressively larger penetration depths.

REVIEW OF EXPERIMENTAL SETUP

The experimental setup of the drawbead test and the tool geometry are illustrated in Fig. 1. The bead cavity has a height of 10.8mm, a width of 13.6mm, and a radius of 4mm for both entry and exit sides. The male bead is separated into a clamping binder and a punch. The clamping binder is to hold the sheet metal and its position is controlled by a kiss block. The height of the kiss block H is the total of the sheet metal thickness t and a pre-determined gap g , $H=t+g$. The bead punch is

10.8mm wide with 4mm radii at the corners. The penetration depth of the bead can be precisely controlled in order to yield different bead restraining forces.

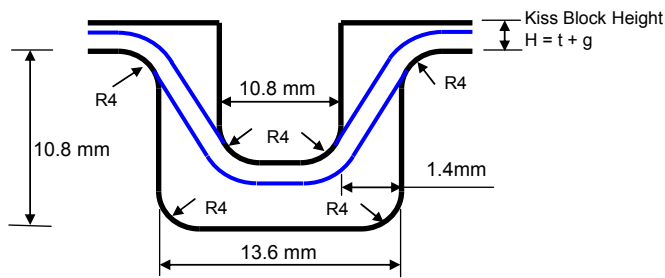


Figure 1. Drawbead Geometry and Setup

During the test, a long strip of sheet metal of 10" (25.4mm) wide was first placed on top of the female bead, which was fixed in position during the test, and clamped to the height of the kiss block. The bead punch then traveled down to a pre-determined penetration depth and remained in the same position thereafter. The metal strip was then pulled through the drawbead. The metal deformation would reach a steady-state after initial transition period. The drawbead restraining force (the pulling force) was recorded, along with measurements of final metal thickness and major/minor strains.

Several steel grades were tested during the "Enhanced Forming Limit Diagrams" project, including Cold-Rolled AKDQ, Cold-Rolled HSLA350, and Hot-Dipped DP600, all with a thickness of 1.2mm. The results for CR AKDQ steel are selected for the current study to illustrate the need for a nonlinear friction model in order to accurately predict drawbead restraining forces, and for sheet metal forming simulation in general. A careful measurement indicated that the sheet thickness of the used CR AKDQ was $t=1.198\text{mm}$, and the gap setup is $g=0.392\text{mm}$, making the height of the kiss block $H=1.59\text{mm}$. Table 1 in the Appendix lists the obtained experimental results. Notice that the actual bead penetration depth is the difference between the bead height and the gap.

MODEL SETUP

A simulation model is constructed to investigate whether the drawbead restraining force (DBRF) can be accurately predicted, and if not, what can be done to improve its predictive capability. Since the metal strip is 25.4mm wide, much larger than its 1.2mm of thickness, it can be safely assumed that plane strain condition dominates its deformation. Therefore a plane strain model is constructed using commercial finite element analysis software ABAQUS/STANDARD. 4-node element with reduced integration is employed. The sheet metal is discretized into 7 layers of elements across its

thickness, and the meshes are also sufficiently fine in the metal strip direction to maintain close to 1:1 aspect ratio (Fig. 2).

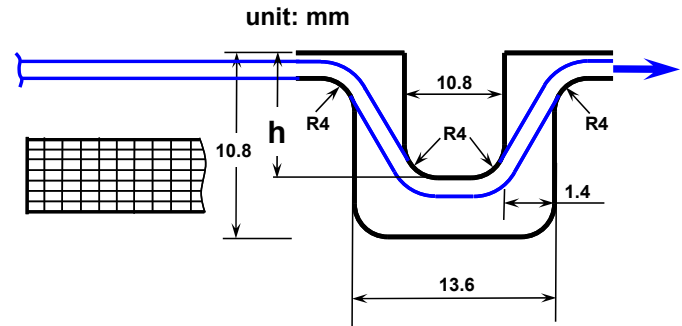


Figure 2. Finite Element Model for Drawbead Pulling Test

The uniaxial tensile data for the CR-AKDQ steel used in the test were plotted in Figure 3. It included tensile curves in three orientations: the rolling direction (0°), the transverse direction (90°) and the diagonal direction (45°). It can be seen that the steel has almost exactly the same tensile curves in the rolling and transverse directions while differs in the diagonal direction. For simplicity, we will treat the material as isotropic and use its 0° tensile property only. A power law fit of the curve gives the effective stress-strain relationship:

$$\sigma = 550.8\epsilon^{0.2215} \text{ (MPa)} \quad (1)$$

which will be used for all the simulations in this study.

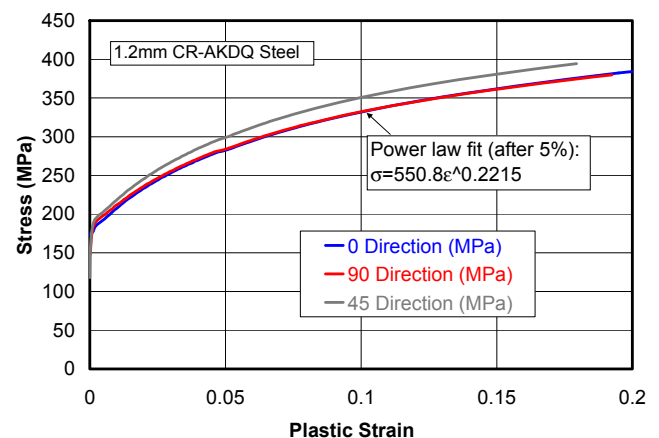


Figure 3. Tensile Curves for CR AKDQ Steel

Eight configurations of bead height h are conducted in the simulations, matching the experimental setup reported in Table 1. Their relative positions are shown in Fig. 4.