

Finite Element Modeling of Dissimilar Metal Self-Piercing Riveting Process

Li Huang

Nanjing University of Aeronautics & Astronautics

John V. Lasecki

Ford Motor Co.

Haiding Guo

Nanjing University of Aeronautics & Astronautics

Xuming Su

Ford Motor Co.

ABSTRACT

In present paper, the process of joining aluminum alloy 6111T4 and steel HSLA340 sheets by self-piercing riveting (SPR) is studied. The rivet material properties were obtained by inverse modeling approach. Element erosion technique was adopted in the LS-DYNA/explicit analysis for the separation of upper sheet before the rivet penetrates into lower sheet. Maximum shear strain criterion was implemented for material failure after comparing several classic fracture criteria. LS-DYNA/implicit was used for springback analysis following the explicit riveting simulation. Large compressive residual stress was observed near frequent fatigue crack initiation sites, both around vicinity of middle inner wall of rivet shank and upper 6111T4 sheet.

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INTRODUCTION

Government regulations and customer demands call for design of ever higher efficiency vehicles and thus wide usage of lightweight materials such as aluminum, magnesium and polymer composites in vehicle body structures. Components built using these lightweight materials need to be joined to steel parts, or to each other. Traditionally, fusion welding processes, such as resistance spot welding (RSW), have been used extensively in assembly process to join vehicle components. These welding processes, however, have some inherent issues when dissimilar materials are involved and alternate joining methods need to be explored. SPR is such a leading alternative. A SPR joint is produced by piercing a tubular rivet into two or more substrate materials. The hard rivet manufactured from advanced high strength steel is pierced through the top sheet/sheets of materials to be joined. It expands in the bottom sheet to form a mechanical interlock. SPR joints have excellent mechanical properties and high fatigue strength [1], and have been increasingly applied by automobile manufacturers in vehicle body assembly.

Although SPR has been employed in vehicle since 1990s, there are still limited publications discussing the process simulation. Numerical simulation of process is important as it is efficient way for evaluation of quality and performance of SPR and could potentially reduce numerous trial-and-error tests during process development. Process simulation is also the means to investigate 3D residual stress field in the SPR joint due to large local plastic deformation and cutting of material that occurs during the riveting process. Residual stress is critical for a fully understanding of the mechanical behavior of SPR connections both for static and durability performance.

Traditional methods such as trial-and-error tests or empirical knowledge-based procedures have been conducted by Fu and Mallick [2] to evaluate the quality of SPR. Numerical simulation of SPR is an alternative way. A key issue in numerical simulation of SPR riveting process is how to define the separation of upper sheet before the rivet penetrates into lower sheet. Generally, geometrical approach or element erosion technique [3-4] could be applied for the material separation. For geometrical criterion, critical minimum thickness of upper layer, at which the sheet would separate, needs to be

defined. However, it is not practical to determine such minimum thickness in real situation and it might also introduce unreal large stiffness response during riveting process. As for the element erosion model, material failure criteria need to be defined in the constitutive models. When the fracture criterion is satisfied, the element is to be removed from the calculation. However, improper failure criterion can lead to unreal volume loss or wrong crack growth path, which could cause an apparent inconsistency between the simulation and experiment results. Currently only a few criteria such as the maximum effective strain criterion [6, 7, 8, 9, 10] or energy based models [11-12] have been applied to SPR forming process and the consistency between simulation and tests still needs great improvement. In addition to the erosion criteria, the continuum damage mechanic models [4,13-14] could also be introduced, which use the notion of effective stress to represent the actual stress transmitted by the bulk material between micro defects, but such empirical or phenomenal critical damage values are usually difficult to measure.

In this paper, the riveting process of SPR joints was investigated numerically and experimentally. Numerical simulation of SPR riveting process with different classic fracture criteria in absence of geometrical failure criteria were performed and compared in LS-DYNA/explicit, and then springback analysis was also conducted in LS-DYNA/implicit. The profile of cross-sections, punch force-displacement curves, and distribution of residual stress were used for verification.

SPR RIVETING PROCESS

During riveting process, the rivet pierces through the top sheet by a punch and expands in the second sheet and forms a mechanical interlock with a die. The riveting process of SPR can be described with following four steps [15]: clamping, piercing, flaring, and releasing, as illustrated in Figure 1. The difference between SPR and conventional riveting is that SPR does not require a pre-drilled hole, and it also brings great benefits in terms of production cost reduction and ease of automation.

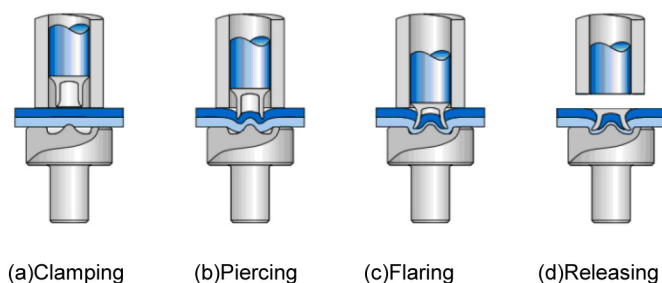


Figure 1. Self-piercing riveting process [16]

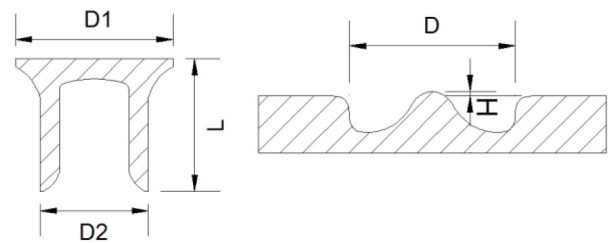


Figure 2. Geometry of the rivet and die

Table 1. Basic parameters of SPR riveting process

Upper sheet 6111T4	Lower sheet HSLA340	Rivet			Die	
Thickness (mm)	Thickness (mm)	D_1 (mm)	D_2 (mm)	L (mm)	D (mm)	H (mm)
1.5	2.4	7.8	5.3	6.5	9	0
2.5	2.4	7.8	5.3	7	9	0

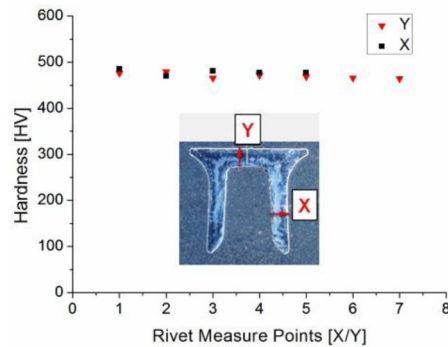
In present paper, all SPR specimens were made of 6111T4 and HSLA340 sheets, and riveted by HENROB servo-electric riveting equipment using 36MnB4 rivets with a countersunk head and zinc coating. Characteristic dimensions of rivet include rivet length L , diameter of head D_1 , and diameter of shank D_2 , while the die is made of steel and has two key variables: diameter of die, D and tip height, H . Geometry of rivet and die are shown in Figure 2 and Table 1 summarizes the basic process parameters.

MATERIAL PROPERTIES

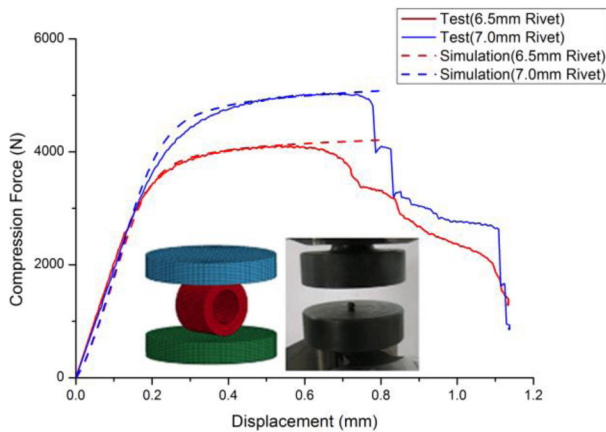
To identify the material properties of the sheets and rivet, material tests were conducted. The base materials were cut from aluminum alloy 6111T4 and Steel HSLA 340 sheets along the rolling direction. The material properties of sheets were obtained through uniaxial tensile tests, and fitted with power law hardening rule.

Two different types of rivets were used in riveting process as listed in Table 1, and they have different length and hardness. Before riveting, the micro-hardness of two typical zones, including the area along the axis of symmetry (Y) and the rivet leg (X) as shown in Figure 3(a) were measured for rivet with 6.5mm length. The micro-hardness measured indicates that the rivet material seems homogenous. However, the rivet material property could not be inferred from hardness directly, so an inverse modeling approach proposed by Porcaro, R., et al. [3] was introduced. The rivet shank was used for the lateral compression test and the compression test was simulated by LS-DYNA/explicit. The rivet material used in the simulation was defined as a piecewise linear isotropic strain-hardening material with assumed initial parameters. These parameters were adjusted iteratively. Final comparison between numerical and experimental results achieved in this way is shown in Figure 3(b), and their force-displacement curves fit quite well. Since no rupture of rivet occurs in common riveting process, the differences between two force-displacement curves close to material failure could be ignored.

The material constants of sheets and rivet are listed in Table 2, where E is young's modulus; $\sigma_{0.2}$ is the yield stress; UTS is the ultimate stress, E_t is the tangent young's modulus; K is the strength coefficient and n is the hardening exponent. All stresses listed are true stress.



(a)



(b)

Figure 3. Material characteristic tests of the rivet (a) micro-hardness analysis of 6.5mm Rivet, (b) lateral compression tests

Table 2. A summary of basic material properties

Material	E (Gpa)	$\sigma_{0.2}$ (Mpa)	UTS (Mpa)	E_t (Mpa)	K (Mpa)	n
6111T4	70	135	366	-	408	0.18
HSLA340	200	344	690	-	596	0.14
Rivet 6.5mm	150	1500	-	1250	-	-
Rivet 7.0mm	180	1750	-	1650	-	-

FE MODELING

A 2-D axisymmetric numerical finite element model of the process was performed with LS-DYNA/explicit.

The initial configuration of the riveting process is shown in Figure 4. The punch, blank holder and die were treated as rigid, whilst the materials of the rivet and the bottom sheet were modeled as elastic-plastic materials with certain failure criteria. The automatic surface contact algorithm with penalty method was adopted, and the law of coulomb friction was used as a friction model. A mesh size of 0.05mm×0.05 mm was same for all deformable parts, and r-adaptivity remeshing method [5] was also added to ensure a reliable solution. A typical duration of riveting of SPR is 0.05 sec, but in simulation the riveting speed was artificially increased 50 times to greatly reduce the CPU time. Despite that, internal energy remained dominant and hourglass energy never exceeded 5% of total energy through whole riveting process. More details could be found in Table 3.

Usually a geometrical failure criterion [4] could be used to define the separation of upper sheet. When the upper sheet thickness reaches a user-defined value, the sheet would be piercing through automatically. For SPR, a typical value 0.2mm might be given for the upper sheet thickness between 1.5mm and 3.5 mm to ensure the stability of simulation. However, such method is not physically meaningful, and extremely hard to determine in real situation for different combination of materials and thicknesses of sheets. In order to build to a reliable and universal approach, various non-coupled ductile failure criteria without artificial geometrical criterion were applied and compared, and these will be discussed in next section.

To avoid severe element distortion caused by classical Lagrange method, an adaptive re-meshing algorithm was adopted to refine the mesh through the explicit analysis to improve element quality dynamically. Springback analysis followed the riveting simulation in full implicit mode using the "dynain" file, which includes stress and node information and was generated during explicit analysis. Specifically, selected nodes were constrained to prevent rigid movement, and double precision version of LS-DYNA was used in springback analysis for accuracy requirement and stable convergence.