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Finite Element Analysis of Self-Pierce Riveting Process

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Abstract-The increasing demands of energy efficiency and lightweight construction in automobile industry led to development of sheet material joining techniques such as self piercing riveting, mechanical clinching. The body in white of vehicle on an average account for about 25-30% of total vehicle weight. Thus, a mixture of lightweight materials like aluminum and high strength steel is increasingly used in automobile applications. In a structure, joint is considered to be the weakest part, so it should be strong enough to hold both the sheets together during the crash loadings. In this work process simulation of self piercing riveted joint of aluminum sheets (A6060 T4) is validated with the help of FEA softwares. Parametrical study is performed to get best possible results with good mechanical interlock of two aluminum sheets.

Keywords- Self piercing riveting, clinching, crash loadings, process simulation, mechanical interlock

I INTRODUCTION

The requirements for energy efficiency and lightweight construction in automotive engineering rise steadily. A mixture of different lightweight materials like aluminum, magnesium, composite materials and higher strength steels, called multi-material mix, is used increasingly to fulfill these requirements and reduce the weight of the vehicles. This results in reduction of fuel consumption and therefore lower carbon dioxide emissions. But it's very challenging to join single components of different materials to the load bearing body in white. The mechanical joining technique has the advantage to make connections stable and reliable, without decreasing the material properties through thermal influences i.e. in case of welding processes. Therefore a lot of mechanical joining techniques like self piercing riveting (SPR) and clinching are used in the automobile production besides the conventional spot welding technique.

Traditionally, resistance welding and fusion welding have been used in the automotive industry. Welding demands localized heating of the material, which may lead to lowering of the mechanical properties of the alloys and base materials. It is not always possible to achieve the required quality of joints in the automotive industry when classical methods of joining like resistance spot welding and laser brazing are used. Thus, some of joining techniques are becoming popular which are alternatives to traditional joining techniques. Thus, this approach raised need of understanding the behavior of joints to ensure efficiency, safety and reliability of joint structures.

R. Porcaro and A. G. Hanssen [1] studied how to perform numerical simulation of self-piercing riveted joint using LS-DYNA and a study was made to suggest the optimum values for parameters like friction and adaptive interval. They developed a new device at the SIM laboratory to record force-deformation history for riveting process. Al 6060 T4 sheets were used for joining. This simple specimen geometry can be tested under different loading combinations in the test set-up presented by

R. Porcaro. Good agreement was found between experimental and numerical data. A mesh sensitivity study was investigated with different combinations of mesh sizes and adaptive intervals. Robert Cacko [4] presented review of material separation criteria in MSC software for numerical modeling of SPR process. Both numerical and experimental tests have been carried out and good agreement is found in the results. Xiaocong He [5] also studied an implicit solution method with Lagrange technique and r-self-adaptivity for SPR process simulation. N. H. Hoang and his colleagues [2] investigated the mechanical behavior of a riveted connection using an aluminum rivet under quasi-static loading conditions (i.e. combined pure shear and pure opening loads). Numerical model of the SPR process were modeled in the following way: the punch, blank holder and die were assumed to be rigid, while the material on the rivet and sheets which undergo plastic deformation during the riveting process were modelled as elastic–plastic materials, adopting an isotropic strain-hardening rule, and the associated flow rule in the plastic domain (MAT_MODIFIED_JOHNSON_COOK). Contact was modelled using an automatic 2D single surface penalty formulation available in LS-DYNA. A Coulomb friction model was used at the interface between each part. In a study conducted by Abe and Mori [3] to join, three high strength steel or aluminum sheets have found that the joining is difficult as the strength of sheets which are to be joined increases, this problem can be solved by optimizing the shape of the die which is used in riveting. As the diameter of the die cavity and depth of central projection increases, the punch load decreases and these results are examined through finite element simulation and found that with optimized die the rivet was able to penetrate through upper and middle sheets to form a proper interlock.

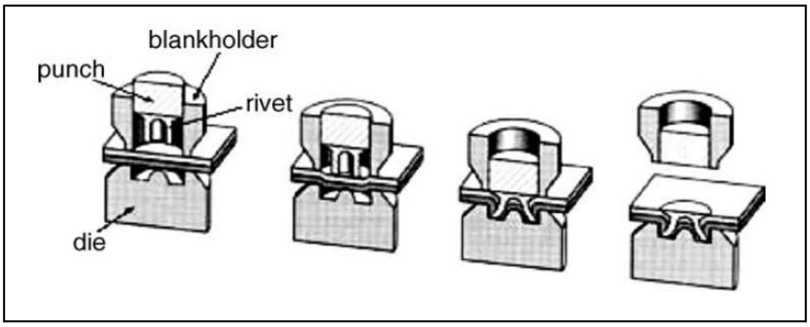

Figure 1. Self-Pierce Riveting Process [2]

Self-piercing riveting (SPR) is a method of joining two pieces of material using a rivet. Unlike conventional riveting, self-piercing riveting does not require a pre-drilled hole, because the rivet makes its own hole as it is being inserted. This brings great benefits in terms of production cost reduction and ease of use compared to conventional riveting. The different stages involved in the riveting process as illustrated in figure 1 are explained as follows [2]:

- Initially rivet is placed just above the sheets that are to be joined
- Punch drives the rivet and penetrates into the upper sheet
- Upper sheet split into two parts and then rivet penetrates into lower sheet and starts flaring.
- An interlock is formed in between both the sheets.

II. METHODOLOGY IMPLEMENTED

The main objective of this section is to carry out the riveting process simulation with the help of finite element techniques.

2.1. Finite Element Model of SPR Process

The SPR process has been numerically solved using the commercial FEA software LS-DYNA. The steps followed during simulation process are listed below

- 2D modeling of parts in SPR process, i.e. rivet, punch, die, blank holder and aluminum sheets was performed in CATIA v5. Dimensions of the die and rivet were obtained from Bollhoff standards. Die and rivet curvatures were modeled carefully because it affects on the joint shape and depth of penetration (figure 2)
- Preprocessing (i.e. FE modeling) of SPR process tools was generated using Altair Hypermesh 11.0 (figure 3)

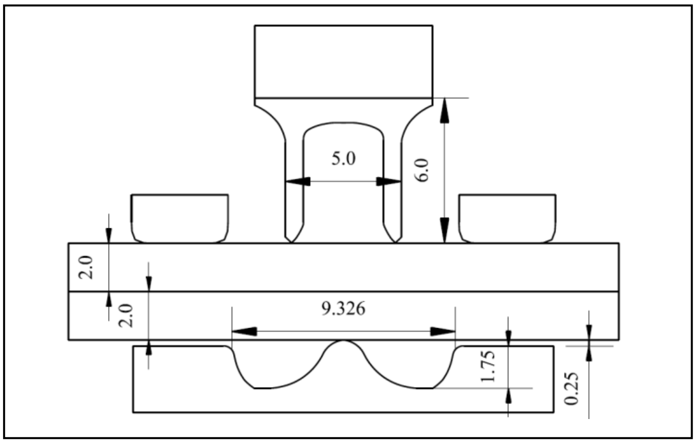

Figure 2. Geometry and Dimensions of SPR Tools (All dimensions in 'mm')

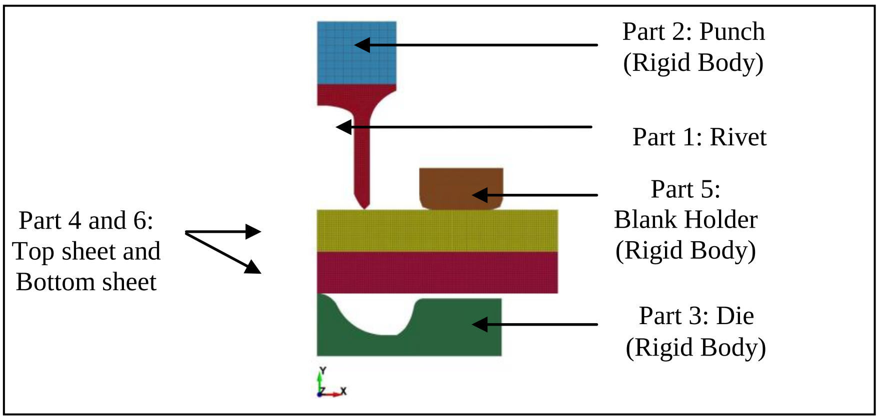

Figure 3. Finite Element Model of Self-Pierce Riveting Process

The self piercing riveted joints, elements undergo large deformation that may lead to error termination i.e. distorted elements. 2D axisymmetric simulation is used in this study to save computational time with desired accuracy. An explicit solution technique with Lagrange method and r-self-adaptivity is used. Thus r-adaptive meshing technique suggested for following reasons [6]

- R-adaptive type of meshing provides an optimized aspect ratio with the same number of elements and nodes by adjusting nodal positions.
- The old mesh is transformed into optimized new mesh by using the least square approximation technique.
- 2D axisymmetric simulation should be used with r-adaptive meshing technique.

The model comprises of six parts viz. (1) Rivet, (2) Punch, (3) Die, (4) Top plate, (5) blank holder, and (6) Bottom plate. The punch, blank holder and die were assumed to be rigid, while the material of the rivet and sheets which undergo plastic deformation during the riveting process were modeled as elastic– plastic materials. Finite element model for parts viz. Rivet, top and bottom plates were made with the mesh size as 0.1mm × 0.1mm. For rivet mesh density is maintained to get the cylindrical profile of the rivet according to the standards. Here the problem is 2D axisymmetric thus, element formulation in keyword SECTION_SHELL with Eq. 14: axisymmetric solid (Y-axis of symmetry) - area weighted is used. [4]

The Eq. 14 element formulation for each part is specified in the keyword SECTION_SHELL under ELFORM option. The default option four-node 2D axisymmetric elements have been used with four Gauss points because of the axisymmetric simulation technique. [5]

2.2. Material properties

The material model with keyword MAT_RIGID/MAT_020 in LS-DYNA was used to represent rigid tools, i.e. punch, die and blank holder. This material model for rigid tools also comprises of material properties and boundary conditions as per requirement of SPR process. The material model with keyword MAT_PIECEWISE_LINEAR_PLASTICITY/ MAT_024 in LS-DYNA was used to represent the rivet and sheet metals. The material model follows Cowper-Symonds model affects the material properties with strain rate consideration. In equation σ_0 is the yield stress with constant strain rate $\dot{\varepsilon}^t$ is the effective strain rate, C and P are parameters of strain rate, $f\ \varepsilon_{eff}^{P}$ is the hardening coefficient based on effective plastic strain. [5]

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}^t}{C}\right)^{\frac{1}{P}}\right] \sigma_0 + f\ \varepsilon_{eff}^{P} \tag{2.1}$$

Table 1. Material Properties [1]

Material	Mass Density (N/mm^3)	Poisson's ratio	Young's Modulus E (MPa)	Yield Stress (MPa)	Ultimate Stress (MPa)
Al 6060 T4	2.8×10^{-9}	0.3	69910	73	180
Rivet	7.8×10^{-9}	0.3	188000	1520	1466
Rigid Tools	7.8×10^{-9}	0.3	210000	-	-

2.3 Contact condition

CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE keyword was used to define the contact between different parts, defined as master and slave. The keyword PART represents various parts in SPR simulation process [6].

Table 2. Static and dynamic friction coefficients

SIDS	SIDM	FM	FD
5	4	0.15	0.15
4	3	0.15	0.15
5	2	0.3	0.3
6	5	0.15	0.15
5	1	0.3	0.3

The part ID was used to identify the master (SIDM) and slave segments (SIDS). The rigid tools are master in this process and deformable bodies are slave because it has to follow the shape of master bodies. The static and dynamic friction coefficients are specified as above in the Table 2.

2.4 Boundary conditions

Displacement is provided to the punch tool enforcing displacement on rivet using the keyword BOUNDARY_PRESCRIBED_MOTION_RIGID. This was done to ensure that the punch tool does not impact the rivet towards the blank, which cause inertial effects resulting in erroneous results. The desired loading force was applied to the aluminum sheets to stay clamped before riveting process starts. Loading force was defined using LOAD_RIGID_BODY card [1].

2.5 Forming time and adaptivity

Self pierce riveting is basically categorized as a cold forming process performed with low velocity. Simulation of SPR process is computationally time consuming if executed on the same time scale. Hence, explicit time integration technique was preferred to simulate the process. Nevertheless, care should be taken to guarantee that inertia forces do not affect the simulation process.

Adaptivity is triggered by varying the angle between adjacent elements. The R - Adaptivity method utilized during process simulation to obtain maximum accuracy for provided problem. In CONTROL_ADAPTIVE keyword ADPOPT with Eq. 8 represents r-adaptive re-meshing technique. R-adaptive FE modeling technique provides superior accuracy. In this work deformable bodies viz. Rivet, top and bottom plate were adaptive meshed. The adaptive meshing of the part was specified in PART [6]

RESULTS AND DISCUSSIONS

3.1 Comparison of force vs. deformation curves

The finite element simulation results were validated against the experimental test results as shown in Fig. 5. A graphical comparison is carried on between the numerical simulation and test results of force deformation curves from the riveting process.

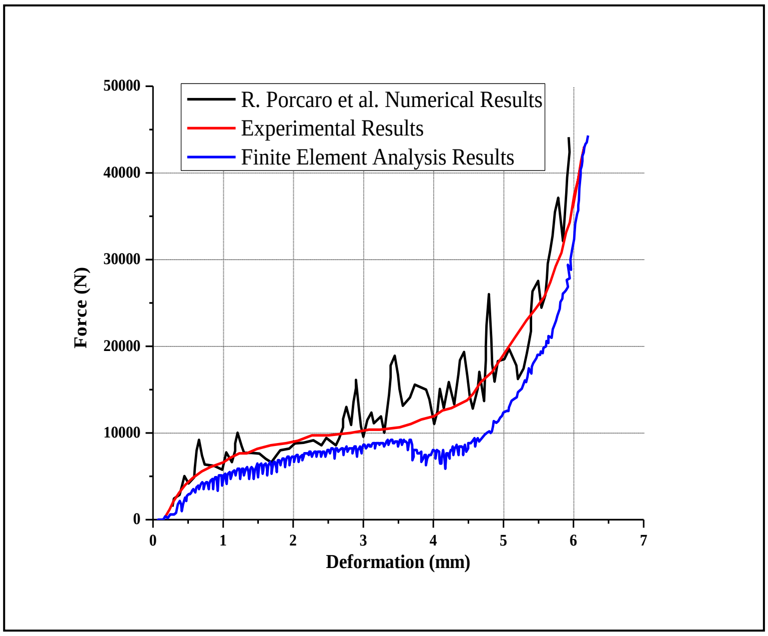

Figure 4. Comparison of force vs. deformation graph

The riveting test results from literature survey were used as a database to validate a 2D-axisymmetric model generated in the explicit commercial LS-DYNA finite element code. Simulations were performed using an explicit solution technique. The re-adaptive method together with a mesh size of 0.1 mm × 0.1 mm was used to deal with the element distortion problem encountered during the riveting process. Effective stresses in the process simulation were plotted as shown in figure 6.

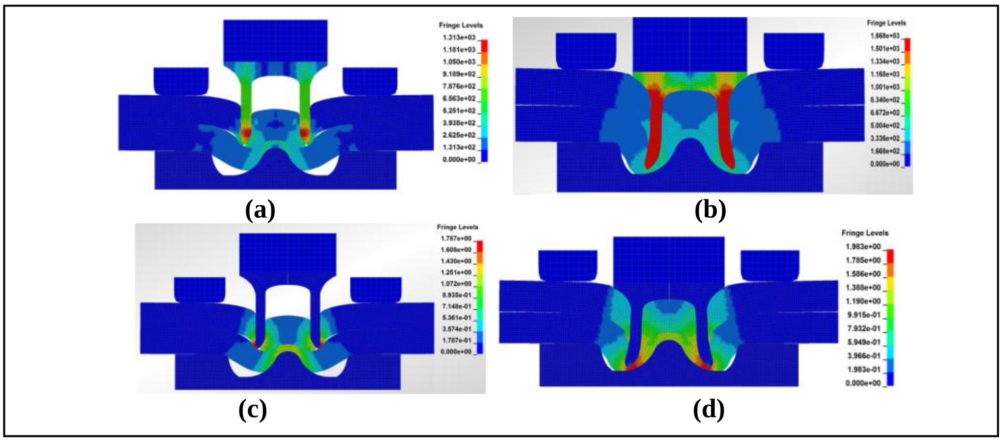

Figure 5. Effective Von-Mises stresses (a) 6.0 Sec (b) 10.0 Sec
Effective Plastic strains (a) 6.0 Sec (b) 10.0 Sec

CONCLUSIONS

The simulation results were between 6-8% variations with the experiments, with respect to the force-displacement curves. The following conclusions were drawn.

1. A finite element analysis of self-piercing riveted connection in Al 6060 T4 of thickness 2 mm is presented in this paper. A simple Bollhoff standard counter sunk rivet is used to establish connection between two sheets. The LS-DYNA explicit finite element code was utilized to simulate the riveting process and the simplification of the riveting process was simulated with an axi-symmetric model.

2. Experimental results were used to validate the numerical results obtained, and slight variations between the results were found. The r-adaptive re-meshing was used to simulate the riveting process in conjunction with failure criterion.

3. Effective Von-Misses stresses were highest in the rivet while effective plastic strains were very high at top plate and bottom plate near centre of the die during separation of plates.

In the next stage of the work tensile, shear and peel test specimens of riveted joints will be tested for different loadings. Experimental testing will be carried out to investigate the strength of the self pierce riveting joint.

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