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Influences of Residual Stresses during Self-Piercing Rivet process on Aluminum sheets using Aluminum Rivets

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Abstract - This Research Paper deals to study the Finite Element Analysis of Self-Piercing Rivet (SPR) forming process using a CAE tool LS-DYNA 971 software. In this software simulation was carried out to understand the simulation of elastic-plastic behavior of aluminum rivet. It was carried out under non-linear condition to investigate the SPR forming process. Aluminum rivet becomes favorable compare to steel regards to some improvement for increasing efficiency in automobile fuel economy and weight reduction. Also wide range of aluminum automotive product such as doors, bumpers, face bars fenders seat frames and roof panels have been produced. In manufacturing industry to minimization of response times and costs and maximization of the efficiency and quality SPR is a major role in product design and development. The major role of Residual Stress in the Self-Piercing Rivet having good response during compression mode in the rivet site and the results are clarified and clearly in this part of analysis.

Key words: FEA, Simulation, Self-Piercing Aluminum Rivet, LS-DYNA, Residual stress

Symbols	ID
FEA	Finite Element Analysis
F	Bending force
L_b	Bend allowance
ρ	Material density
M_{BR}	Minimum bend radius
σps	Yield stress in plain strain tension
E	Young's modulus
K	Numerical constant
L	Contact length

Rd	Die radius
σ_y	Uniaxial yield strength
ε	Strain
t	Sheet thickness
ν	Poisson ratio
R_f	Radius of curvature after spring back
α	Bend angle
W	Width of die
S	Ultimate tensile strength
R_o	Original radius of curvature

1. Introduction

Piercing a rivet in to the sheet metal by applying forging force on rivet through punch without predrilled hole is called self-piercing rivet (SPR). This topic was chosen why because in Automotive Vehicle manufacturing industries facing problem in joining two different material without changing the mechanical, chemical and thermal properties. So this Self-Piercing Riveting method is important in the Automotive Society. This methods is adopted particularly because of the light weight, properties are not changing after joining, more than two layer can be joined easily and also joining quickly. Based on the material various metals were tested in many researcher. Therefore this analysis we chosen aluminum Rivet AA 7075 as a Self-Piercing Rivet material for furthermore analysis of residual stresses. Finally the analysis they discussed many areas example in Finite Element area there we considered the meshing of all the component in the assembly. In the assembly the sequence method was followed and FE techniques was adopted and simulated. In the conclusion the results were predicted and plotted. Ultimately the residual stresses were predicted in the rivet and the sheet metal. Next the images were captured in unsymmetrical manner and placed for display. condition of symmetry that only normal stresses act on the

2. Literature Survey

2.1 Residual Stresses on Self-Piercing Rivet

In 2000, D.A.Tanner & J.S.Robinson, [1] published a paper in which they described about the Residual Stress prediction and determination in 7010 aluminum alloy forgings. The residual stress distributions in two 7449 aluminum alloy rectilinear elements have been determined using neutron diffraction. A square cross section post in the centre of the machined face was left to act as a stress free reference sample. The distortions arising on the face opposite to that being milled were measured using a co-ordinate measuring machine. The residual stresses and distortion arising in the blocks have been compared to finite element analysis prediction and found to generally agree. Material removal only caused distortion and the residual stresses to redistribute; and finally there was no stress relaxation evident.

In 2017, Li Huang et al., [11] demonstrated that the finite-element and residual stress analysis of self-pierce riveting in Dissimilar Metal Sheets. The residual stress profile in dissimilar metal sheets joined by a self-piercing rivet is simulated and compared to experimental measurements. Simulation of joining aluminum alloy 6111-T4 and steel HSLA340 sheets by self-piercing riveting (SPR) is performed using a two-dimensional axis-symmetric model with an internal state variable (ISV) plasticity material model. Strain rate and temperature dependent deformation of the base materials is described by the ISV material model and calibrated with experimental data. Using the LS-DYNA simulation package, an element erosion technique is adopted in an explicit analysis of the separation of the upper sheet with maximum shear strain failure criterion. An explicit analysis with dynamic relaxation technique was then used for spring back and cooling down analysis following the riveting simulation. The residual stress profile of SPR experimental joint with same configuration is characterized using neutron diffraction, and good agreement was found between the simulation and residual stress measurements.

In 2007, Calvin Rans and Paul V. Straznicky., [10] reported that the riveting process induced residual stresses around solid rivets in mechanical Joints. Finite element model consisted of two 1.0 mm thick 2024-T3 plates joined at their centers by a single 3.2 mm diameter 2117-T4 aluminum rivet. Solid rivet introduces a residual stress field beneficial to the fatigue life of riveted joints. The radial expansion process of Self-Piercing Rivet in the jointed sheet during riveting process induced residual stresses beneath the rivet head and the thickness of sheets.

In 2018, J.F.C. Moraes, and et al., [2] pointed to the draws our attention to this work, they briefed the complex relationship between deformation history and residual stresses in a magnesium-to-aluminum self-pierce riveted (SPR) joint is elucidated using numerical and experimental approaches. Non-linear finite element (FE) simulations incorporating strain rate and temperature effects were performed to model the deformation in the SPR process. In order to accurately capture the deformation, a stress triaxiality-based damage material model was employed to capture the sheet piercing from the rivet. Strong visual comparison between the physical cross-section of the SPR joint and the simulation was achieved. To aid in understanding of the role of deformation in the riveting process and to validate the modeling approach, several experimental measurements were conducted.

To quantify the plastic deformation from the piercing of the rivet, micro hardness mapping was performed on a cross-section of the SPR joint. The FE model showed very strong correlation to the experimental hardness mapping results suggesting the nonlinear model captured the plastic deformation with high accuracy. To measure the elastic residual stresses in the SPR joint, neutron and x-ray diffraction mapping techniques were conducted and in general, the FE model correlated well to the trends and magnitudes of the elastic stresses. While some error occurred in between the model and the neutron and x-ray diffraction results, the numerical approach developed in this study shows potential as a tool for understanding SPR behavior as well as optimizing the process parameters.

In 2017, Huang, I et al., [8] has declared the Finite Element and Residual Stress Analysis of Self-Piercing Riveting in Dissimilar Metal.

In 2019, Rezwanul Haquea., et al., 2019, [12] has defined the Residual stress distribution in self-piercing rivet joint of high strength steel. Residual stresses measured in rivets of two different Self-Piercing Rivet Joints using neutron diffraction techniques. It was observed that the stresses that developed inside Self-Piercing Rivet joints was compressive and the magnitude of the residual stress was low in the softer material in compression with the harder material. It was also evident that from the cross-section. The results are discussed based on the movement of the physical materials in Self-Piercing Rivet joining process.

In 2018, R. Haque., [7], The author is reviewed very familiar with the Residual stress in self-piercing riveting (SPR) joints does not require pre-drilling. However, in SPR, the rivet plastically deforms and residual stress develops in the joint. The deformation behavior of the rivet and the residual stress distribution in SPR joints are poorly understood. Development of new rivet and die geometries are also limited since the residual stress state in SPR joints are not fully described. Several key issues in modeling and measuring residual stress in SPR joints are discussed. How the plastically induced residual stress can be linked to the different phases of the riveting process is also described. This is an area of SPR with numerous prospects for research.

In 2012, R. Haque, et al.,[4] is careful to point out that Feasibility of measuring residual stress profile in different self-pierce riveted joints. The main challenge involved dealing with the very small dimensions of SPR joints. Two different joints were examined: aluminium–steel and steel–steel. Even though small dimensions were involved, meaningful results were obtained. In the rivet head, tensile stress was observed for the steel–steel sample, whereas only compressive stress was observed for the aluminium–steel. The residual stress in the rivet head was higher at the centre and lower at the edge for both joints. Stresses in the sheet material beside the rivet wall and at a distance of three times the rivet radius from the rivet axis were not significant. For the SPR joints examined, the maximum value of residual stress was compressive and occurred in the rivet leg. The results are discussed according to the physical events involved during the process.

In 2011, R. Haque and et al., [3] the study states that evaluation of Residual Stress in SPR Joint by Neutron Diffraction. The feasibility of measuring residual stresses in Self-Pierce Riveted (SPR) joints by neutron diffraction was evaluated in this study. Despite the small dimensions involved, meaningful results were obtained. It was observed that residual stress in the rivet head was higher in the centre and lower at the edge. For the SPR joints examined, the maximum value of residual stress evaluated was 550MPa, compressive and occurred in the rivet leg. Stresses in material adjacent to the rivet wall and at a distance of three times the rivet radius from the rivet axis were not significant. The results are discussed with respect to the physical events involved during SPR.

In 2013, R. Haque and et al.,[5] Optimizing parameters for meaningful measurement of residual strain by neutron diffraction in self-pierce riveted joints, Science and Technology of Welding and Joining. The aim of this work is to examine the uncertainties involved in measuring residual strain and their dependence on both the gauge volume of the neutron beam and the acquisition time in self pierce riveted (SPR) joints while using the neutron diffraction technique. The main challenge involved dealing with the very small dimensions of SPR joints and developing optimum instrument configuration that allowed faster and/or more accurate stress measurement in SPR while maintaining the same time resolution required for the millimeter scale of the problem. Two different gauge volumes were used (0.125 and 1.0 mm(3)), and two different measuring directions were chosen in order to examine the rotational accuracy of the sample table. All measurements were conducted in steel joints. Even though small sizes were involved, meaningful results were obtained and measurement errors were reduced by optimizing the instrument parameters.

In 2017, R. Haque, et al., [9] SPR Characteristics Curve and Distribution of Residual Stress in Self-Piercing Riveted Joints of Steel Sheets, Neutron diffraction was used to describe the residual stress distributions in self-piercing riveted (SPR) joints. The sheet material displayed a compressive residual stress near the joint, and the stress gradually became tensile in the sheet material far away from the joint. The stress in the rivet leg was lower in the thick joint of the softer steel sheet than in the thin joint of the harder steel sheet. This lower magnitude was attributed to the lower force gradient during the rivet flaring stage of the SPR process curve. This study shows how the residual stress results may be related to the physical occurrences that happened during joining, using the characteristics curve. The study also shows that neutron diffraction technique enabled a crack in the rivet tip to be detected which was not apparent from a cross-section.

In 2015, R. Haque and et al.,2015, [6] Residual stress profiles in riveted joints of steel sheets, The residual stress profiles in two different self-piercing riveted (SPR) joints were characterized using the neutron diffraction technique. The joints were produced using semi-tubular steel rivets and carbon steel sheets of different thicknesses and harnesses. The residual stress in the sheet material inside the bore of the rivet was compressive at the centre and the stress became tensile away from the centre. The stresses found in the semi-tubular rivet were compressive, with a lower magnitude in the rivet head compared with those in the rivet leg. For the SPR joints examined, the compressive residual stress in the rivet leg was greater for the thin joint than the thick joint, and this was due to the higher force gradient encountered during the rivet flaring stage. The originality of this work was to relate the residual stress profile to the physical event that occurred during the SPR process.

3. Materials and Methods

3.1 Materials

In this study Figure 1 shows a schematic representation of Self-Piercing Rivet coupon employed.

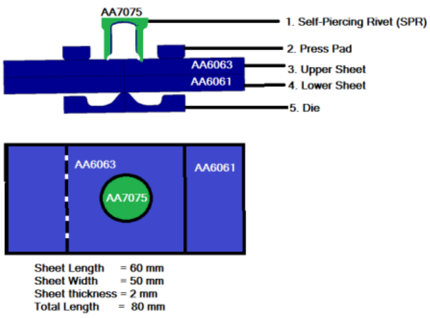

Figure 1 shows a schematic representation of Self-Piercing Rivet

Table : 3.1 Joint Parameters selected for present study

Joint number	Material	Top sheet (mm)	Bottom sheet (mm)	Rivet		Die	
				Length (mm)	Hardness (HV)	Diameter (mm)	Depth (mm)
1	AA6063	2	2	7	555	10	2.1
2	AA6061	2	2	7	550	10	2.1
	AA7075	2	2	7	600	10	2.1

In the Joint parameter table 3.2.1. indicates the different material used to assign real property of the Self-Piercing Rivet and its hardness, with variation of length and diameter.

Aluminum is an extremely versatile metal with various advantages, it is recognized for being both lightweight and flexible material. Aluminum can be cast, melted, formed, machined and extruded meaning that it can be manufactured into a variety of shapes and then subsequently fabricated to suit a whole variety of uses. Aluminum is about one-third the weight of steel, meaning parts can be made thicker and stronger while still reducing weight mainly in automobile vehicles and other applications. Depending on the alloy and processing technique aluminum can be used pound for pound added just as a stronger and stronger. Cost wise a pound of steel is typically cheaper than a pound of aluminum.

Table : 3.2 Joint Parameters selected for present study

Material	Elastic modulus (Gpa) or N/mm2	Yield stress (Mpa)	Tensile strength (Mpa)	Flow stress (Mpa)	Hardening Method
AA6063	70 or 70E5	218.11	152	$\sigma = 310.48.23\varepsilon^{0.057}$	Precipitate hardening
AA6061	68.3 or 68.3E5	205.50	145	$\sigma = 295.82.64\varepsilon^{0.057}$	Age Hardening
AA7075	7.8 or 7.8E5	450.34	572	$\sigma = 470.97.81\varepsilon^{0.057}$	Specially Artificially aged

Table 3.3: Rating power of Forging Press Tools in Self-Piercing Riveting

Types of Forging Ratings	**Mechanical Forging Press Ratings**	**Hydraulic Forging Press Ratings**	**Friction Screw Press Ratings**
Maximum Energy in Kg-m	**210 Tones**	**170 Tones**	**170 Tones**

3.2. Methods

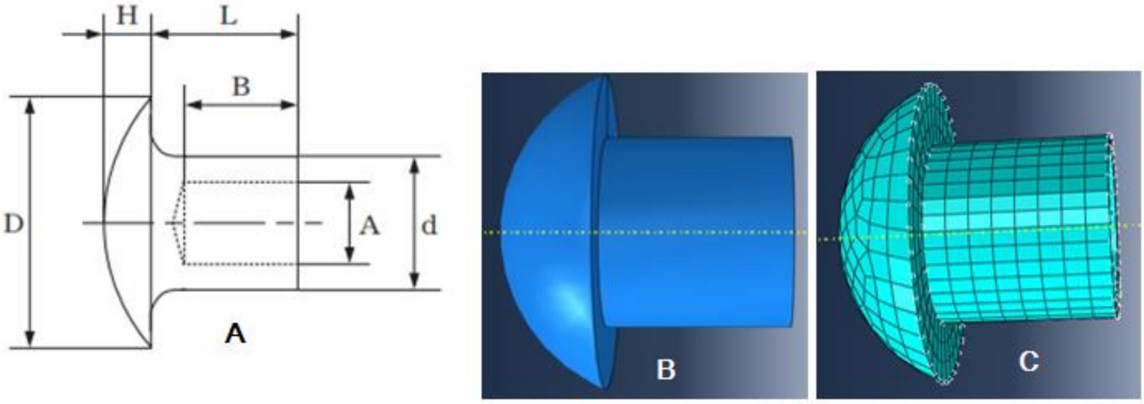

Figure 3.1 Self-Piercing Rivet Models

Figure 3.1 Self-Piercing Rivet Nomenclature [A]and its CAD Model [B] and Finite Element Model [C]

The Figure 1.1 illustrates the ABC images, and its shows the detailed sketch, CAD and FEM of SPR component respectively. In Figure A described the sketch SPR Rivet has the various important parameters such as diameter of head (D), diameter of shank (d) and length of the rivet (L). Other parameters are annular diameter (A), annular shank length (B) and head height (H). In figure B has a CAD model means shape, size and texture shows the major parameters and figure C indicates the finite element model which as nodes and elements generated by the meshing tool.

Table :3.2 Specification of Self-Piercing Rivet

Description	CASE-1	CASE-2	CASE-3
Nominal Diameter, d	5	4	3.6
Tolerance for d	±0.05	±0.05	±0.05
Nominal Diameter, D	9.6	7.4	6.6
Tolerance for D	0 to -0.4	0 to -0.4	0 to -0.4
Head Height H	1.8	1.5	1.2
Tolerance for H	±0.05	±0.05	±0.05
A	2.9	2.4	2.2
B	L x 0.8	L x 0.8	L x 0.8
L	7.0	5.5	4.5

The detailed specification of the Self-Piercing Rivet with three different cases have been shown in Table:1.1

In the FE analysis every frame of simulation captured in the form of graphs and images and also tabulated the required data as results. So that we can justify the captured images can be briefed.

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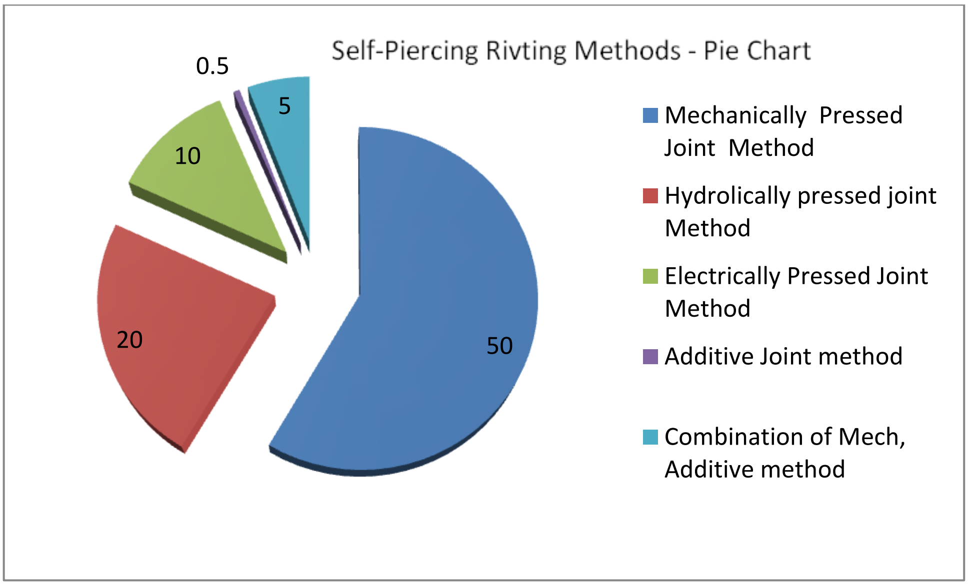

Figure 3.2.1 Pie chart for Self-Piercing Rivet methods

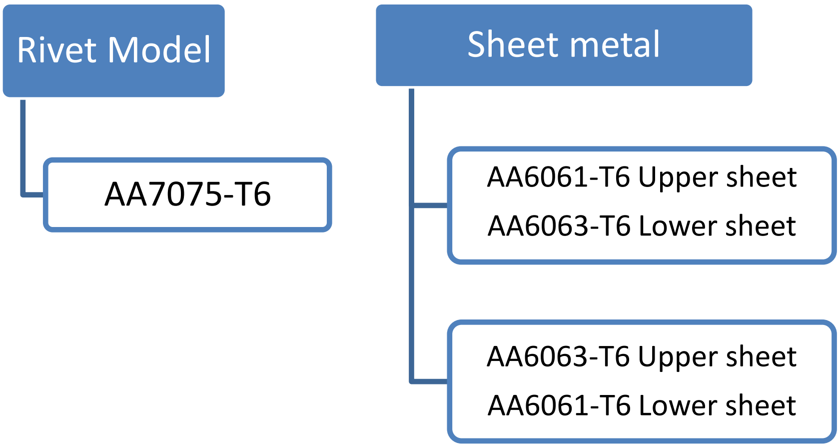

Figure 3.2.2 Illustrate the Material of the Rivet and Sheet metal categories

4. Results and Discussion

Table 4.1: Displacement of Self-Piercing Rivet and its stages with position and Time

Stage	Position	Frame	Time	Maximum Displacement
Stage -1	Initial	1	0	0
Stage -2	Compression-1	125	2.48	6.86E-02
Stage -3	Compression-2	250	4.98	1.53E-01
Stage -4	Compression-3	375	7.48	2.38E+01
Stage -5	Compression-4	501	10	8.63E-02

\

Table 4.2: Residual Stresses of Self-Piercing Rivet and its stages with position and Time

Stage	Position	Frame	Time	Maximum Displacement
Stage -1	Initial	1	0	0
Stage -2	Compression-1	125	2.48	6.86E-02
Stage -3	Compression-2	250	4.98	1.53E-01
Stage -4	Compression-3	375	7.48	2.38E+01
Stage -5	Compression-4	501	10	8.63E-02

4.3 LS-DYNA 971 Simulation

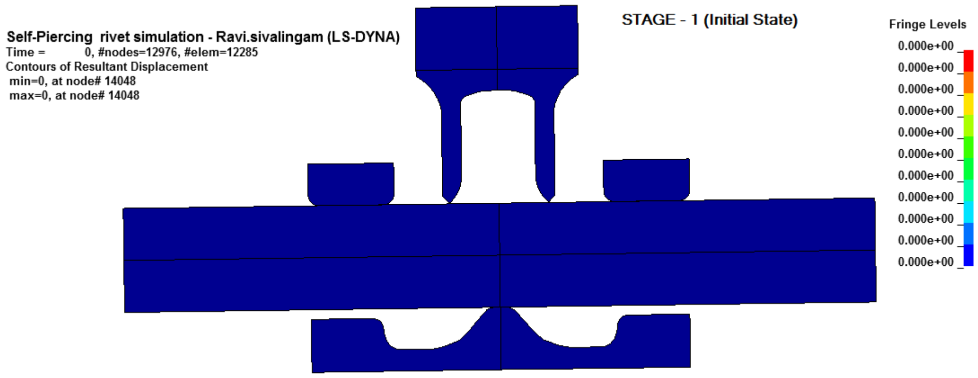

Figure 4.3.1 Illustrates the initial condition of Self-Piercing Rivet Assembly

This section has review the three key aspects of Self-Piercing Rivet joints. Assembly of Self-Piercing Rivet of first stage means no load condition on the rivet. So that the rivet has no changes in the position. The position of the Self-Piercing Rivet, upper and lower sheet with punch and die as shown in Figure 4.3.1.

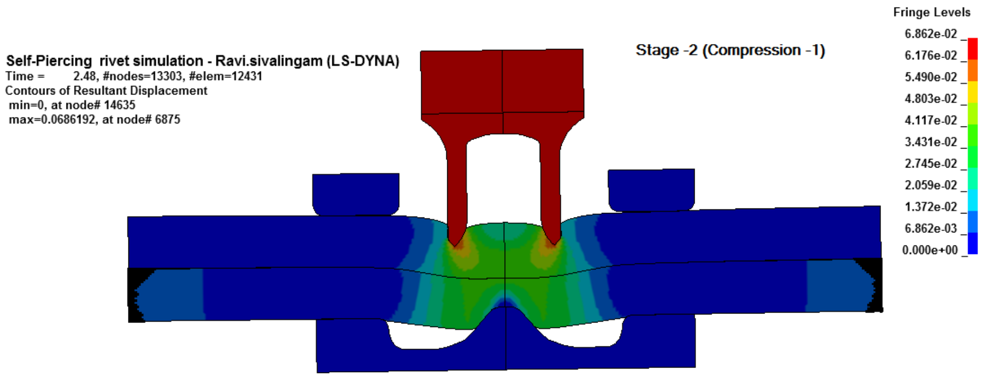

Figure 4.3.2 Illustrates the 125/501 frame condition of Self-Piercing Rivet Assembly

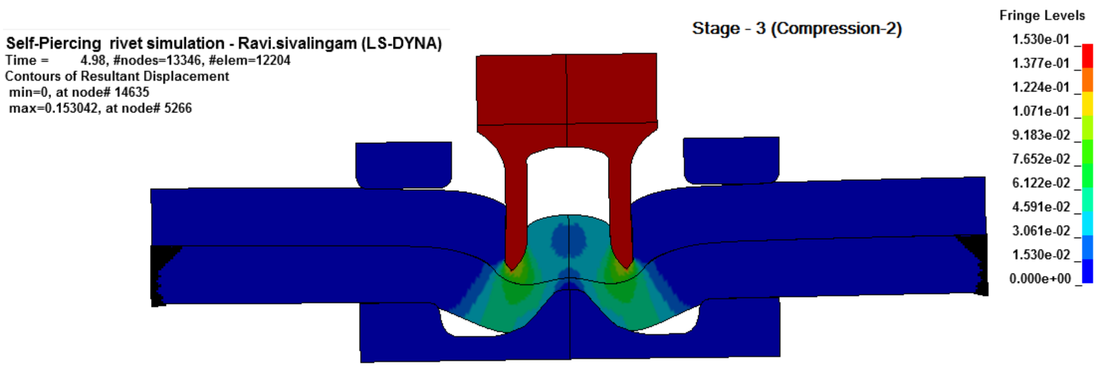

Figure 4.3.3 Illustrates the 250/501 frame condition of Self-Piercing Rivet Assembly

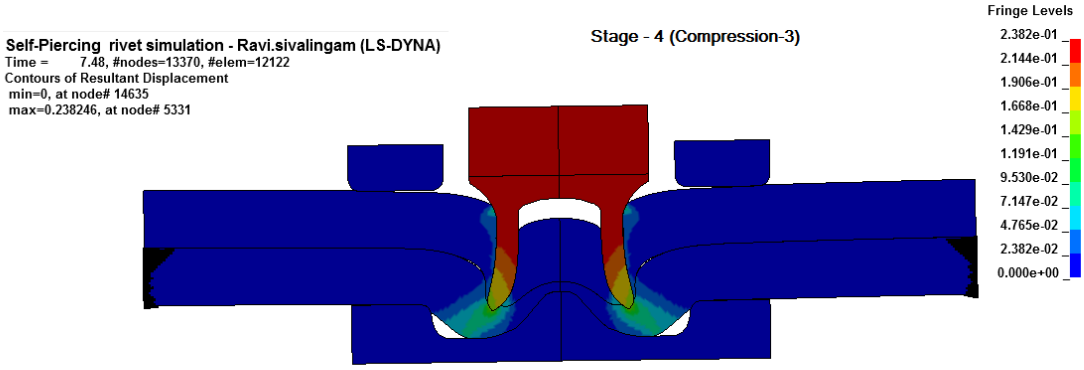

Figure 4.3.4 Illustrates the 375/501 frame condition of Self-Piercing Rivet Assembly

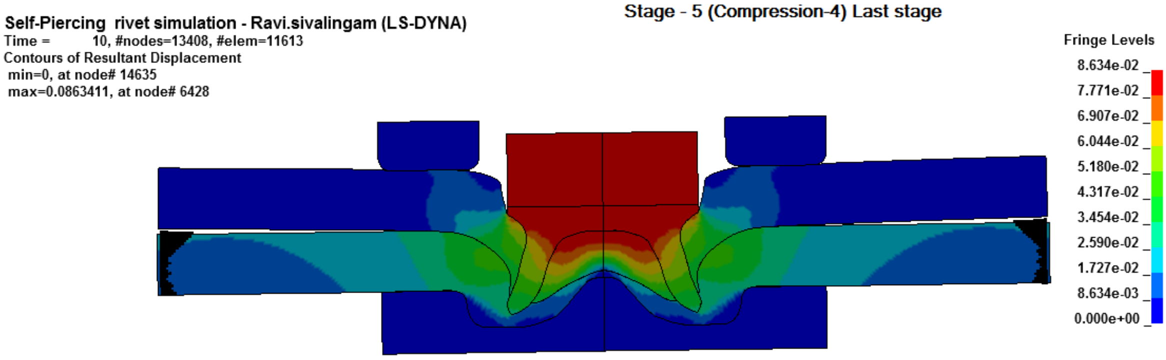

Figure 4.3.5 Illustrates the complete frame end condition of Self-Piercing Rivet Assembly with joint

5. Self-Piercing Rivet Analysis Graphs:

5.1 Displacement Vs Time Plot

5.2 X Rigid Body Velocity Vs Time Plot

5.3 Y Rigid Body Velocity Vs Time Plot

5.4 Axial Force Vs Time Plot

5.5 Temperature VS Time

5.6 Residual Stress Vs Time

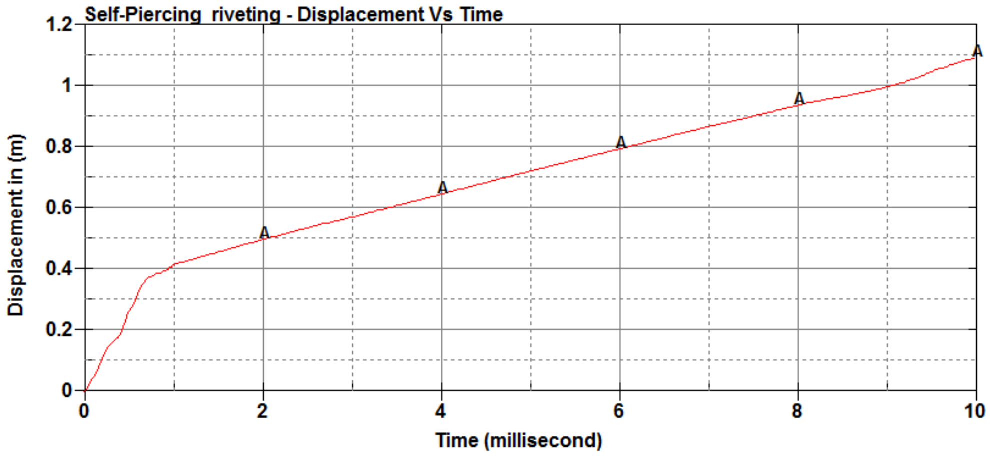

Figure 5.1 Displacement Vs Time Plot

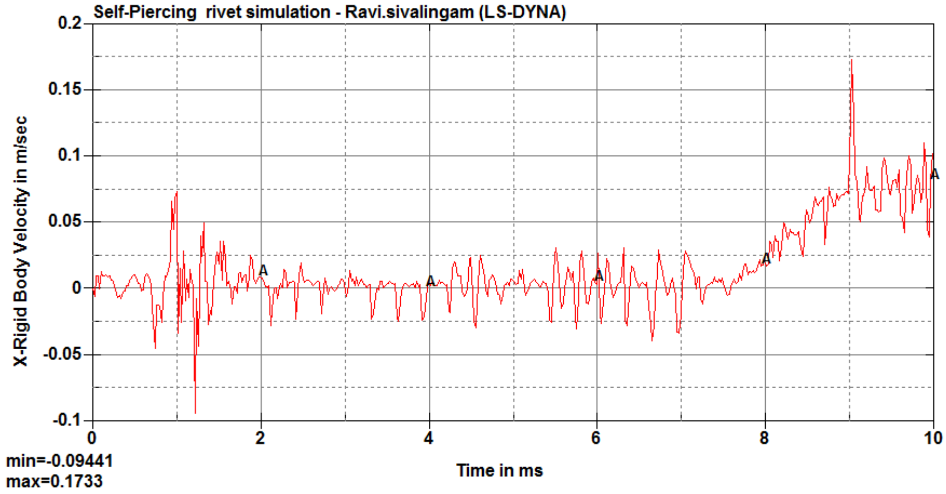

Figure 5.2 X Rigid Body Velocity Vs Time Plot

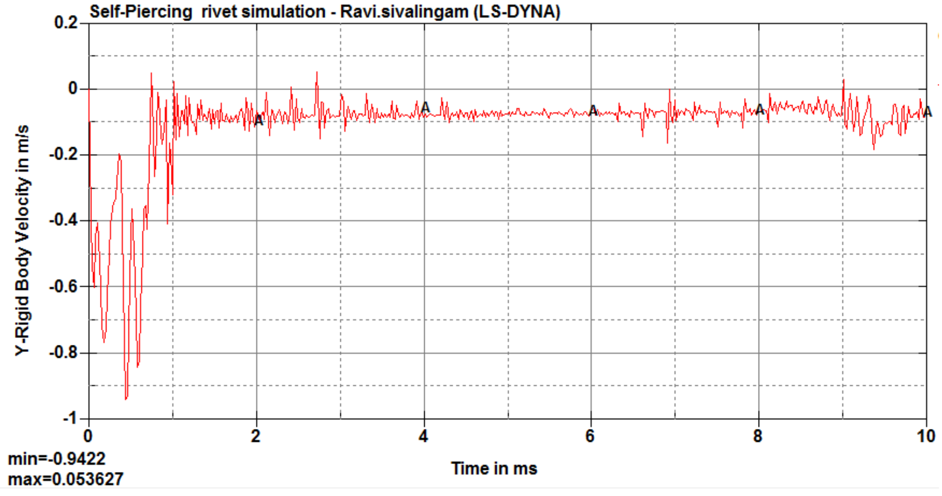

Figure 5.3 Y Rigid Body Velocity Vs Time Plot

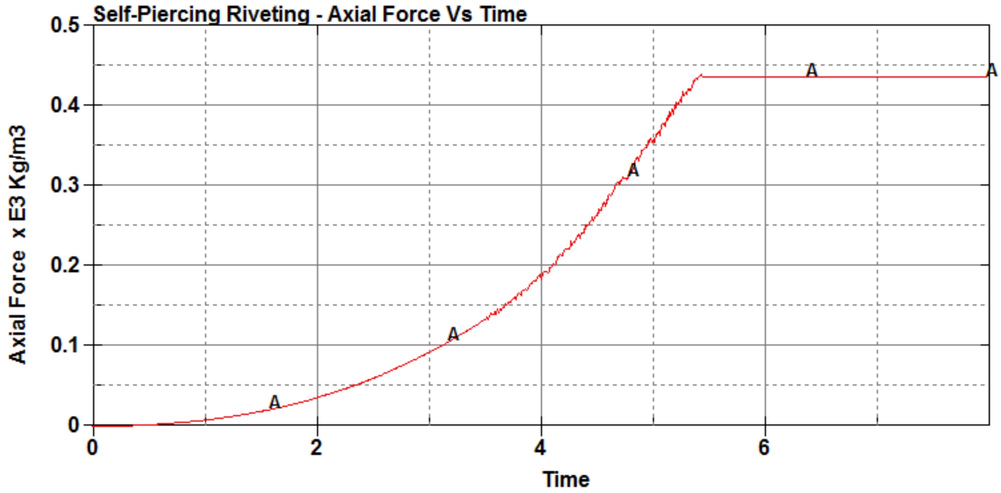

Figure 5.4 Axial Force Vs Time Plot

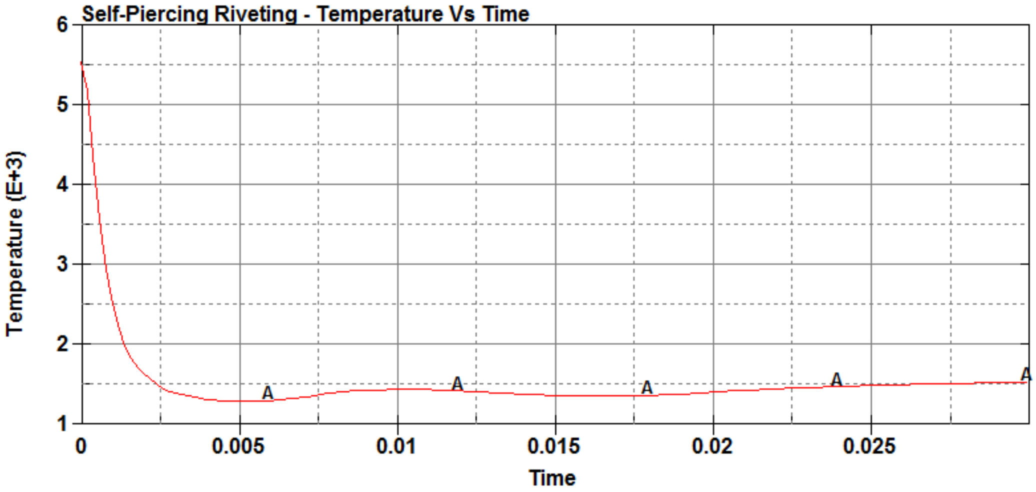

Figure 5.5 Temperature VS Time

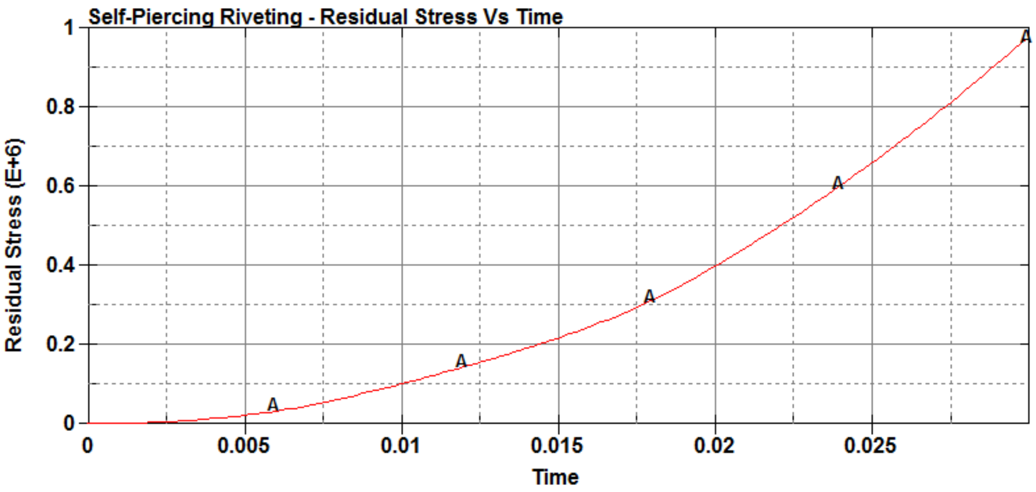

Figure 5.6 Residual Stress Vs Time

Conclusion

The present study the characterization of residual stresses and strain hardening due to the riveting process history in aluminum to aluminum Self-Piercing Rivet joint. The comprehensive study included advanced FE simulation characterization such as Residual stress and time plot, process temperature and time plot, Axial force and time plot, X axis and Y axis with time plot and displacement with time plot illustrate the data structure predicted from the LS-DYNA 971 software after simulation was run from d3plot, we can get the solution and then from the solution we captured the required Self-Piercing Rivet process simulation plots. From this we selected sample nodes at the required point and predicted the residual stresses god and bad residual stresses. The compressive residual stresses on the top of the rivet head was the good residual stresses and bottom edge compiled and taking tensile residual stresses. To date various methods have been developed and introduced to measure the residual stresses. This FE simulation method was a

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