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MODELLING OF SELF-PIERCING RIVETING WITH ALE, CEL AND SPH BASED ON ABAQUS/EXPLICIT

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Abstract. SPR (Self-piercing riveting) is a cold forming process that is used to fasten together two or more sheets of different materials mechanically with a rivet. Also SPR emulates the results and quality of spot welding without many of the risks, such as toxic fumes, sparks and noise. Thus circumstanced, this technique is widely used on the various filed especially within automobile industry. SPR, in particular, is excellent for lightweight manufacturing and for precise working while dramatically reducing cost and production time. The process deformation depends on the sheet size, shape of die, material flow, stiffness, etc. Also material deformation in both of rivet and workpiece sheets is tremendous large, for instance thinning, necking, shear and penetration. Therefore it is very hard to analyze this forming process with FEM which uses normal stress element formulation due to the collapse. On the other hand, Abaqus/Explicit has superb analysis methods, for example ALE, CEL and SPH[1]. This paper investigates several Abaqus/Explicit modeling techniques for simulating and optimizing SPR process. In addition, the effectiveness of these analysis methods was discussed and compared for evaluating SPR process forming in order to achieve an optimal die, material properties and suitability of deformations.

1 INTRODUCTION

For a long time, several joining technologies have been developed for automotive manufacturers to perform weight and cost reduction goals. Among these, SPR is identified with an effective and possible method for uniting some dissimilar panels, for instance aluminum parts and steel parts. SPR is essentially a cold forming operation. A semi-tubular rivet is engaged into two or more sheets of material that are supported on a die and a holder. The rivet pierces the upper sheet and is flared into the bottom sheet, thus mechanical forming interlocks between the two sheets as shown in Figure 1[2]. Also SPR emulates the results and quality of spot welding without many of the risks, such as toxic fumes, sparks and noise. Thus circumstanced, this technique is widely used on the various fields especially within automobile industry. SPR, in particular, is superb for lightweight manufacturing and for precise working while dramatically reducing cost and production time. The process deformation depends on the sheet size, shape of die, material flow, stiffness, etc. Also material deformation in both of rivet and workpiece sheets is tremendous large, for instance thinning, distortion, shear and penetration. Since it is important for the automotive design engineers to understand the mechanical behavior of different SPR joints, furthermore, to incorporate these joint properties in the early design stage using computer aided engineering and design tools.

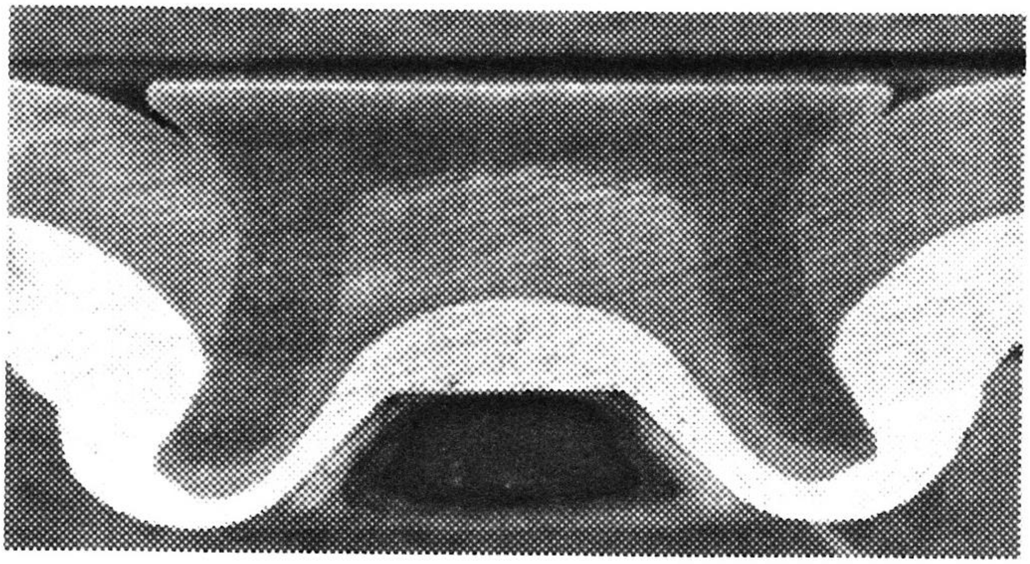
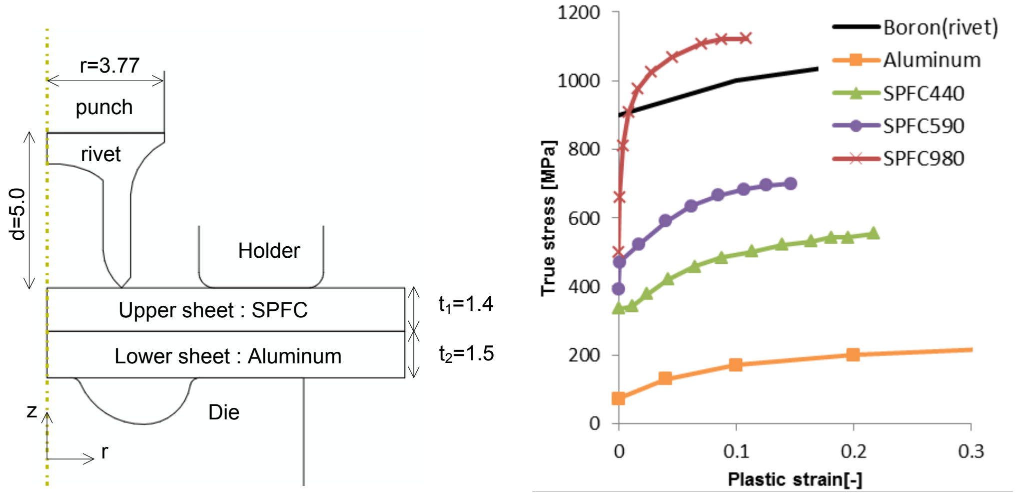


Figure 1: Cross section for experimental SPR forming of 1.4mm SPFC440 (upper sheet) and 1.5mm Aluminum (lower sheet)

2 MODEL DESCRITION

A target axisymmetric section in this research is shown in Figure 2(a). This model consists of six parts of which shapes are conventional design of SPR. Two deformable sheets were put between a rigid holder and a die. Lower sheet was assumed as an aluminum material, and upper sheet was SPFC (Steel Plate Formability Cold). In this paper, we examined three dissimilar flow materials of SPFC for upper sheet. The later three digits of SPFC in the Figure 2(b) mean a minimum tensile strength. Figure 2(b) shows all flow stress curves of all materials, SPFC980 has the largest tensile strength, while aluminum is the most ductile metal. Rivet which was assumed to be a Boron material was placed on the upper sheet and thrusted below by a punch. ALE model was analyzed on this axisymmetric condition, while CEL and SPH were analyzed with 3D models based on this axisymmetric cross section and material condition. Following sections explain each modeling.



(a) (b)

Figure 2: (a) Axisymmetric section; (b) Material flow

2.1 Modeling of ALE

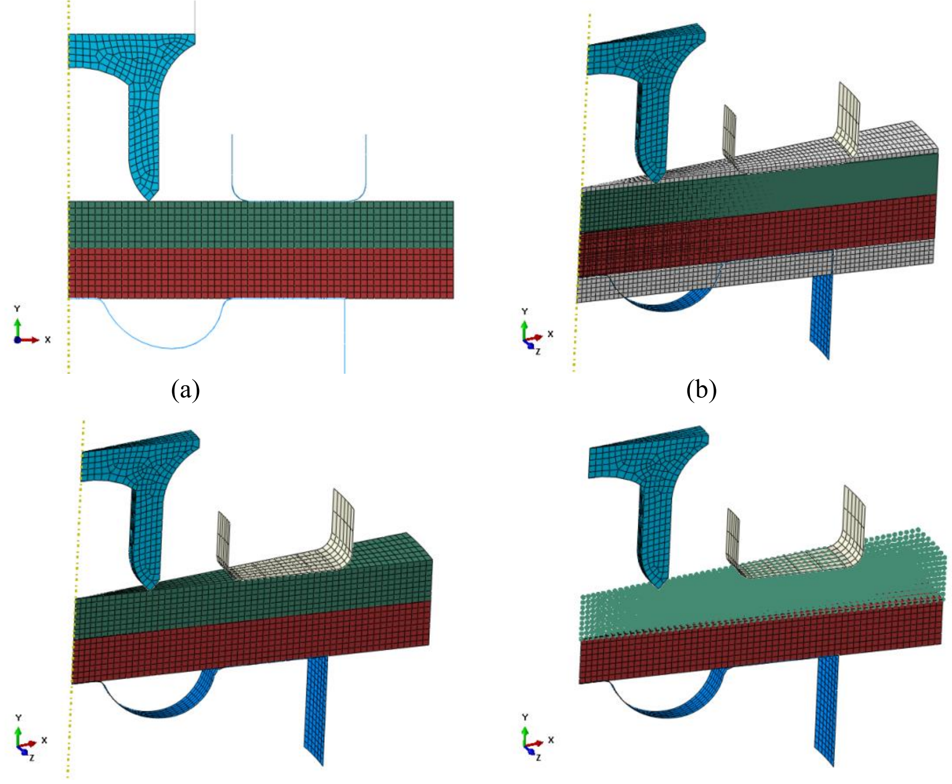
Figure 3(a) shows an axisymmetric ALE model. The element type used in deformable parts such as a rivet and two sheets was CAX4R, while the element type of RAX2 was used in rigid body such as die, holder and punch. Both mesh size of upper and lower sheets was 0.2mm at cross section. The mesh size of rivet was also the same manner. CONTACT PAIR conditions were applied to each contact surface. The velocity of punch was 5mm/s in the minus Y global direction, also one second was taken at the total phenomenon time. ADAPTIVE MESH criteria were applied on the parts of upper and lower sheet, since it was expected that the element of both sheet suffered large shear deformation.

2.2 Modeling of CEL

The modeling of CEL is shown in Figure 3(b). CEL function has to be analyzed only three-dimensional field, therefore this model was comprised of wedge shape of ten degrees. The domain necessary for analysis was occupied in Euler elements EC3D8R with enough space as shown in white mesh. Also discrete field was set for upper sheet with green space by using the volume fraction tool in Abaqus/CAE. In this study, Euler mesh size was adopted 0.1mm at cross section. While two parts of rivet and lower sheet were performed with normal stress element C3D8R of which mesh size at cross section was 0.2mm. Punch speed and phenomenon time were as same as ALE model. To keep wedge shape, local cylindrical hoop boundary condition was applied on the lateral faces on the model.

2.3 Modeling of SPH

The last model in this study was SPH method. This model was also made in wedge style as same as CEL model. Figure 3(c) shows the dummy SPH model which was made with normal solid element C3D8 within the upper sheet space. After it was output as for Abaqus input file, PC3D elements were rewritten by manual operation with an element number same as a node number constituting C3D8. Figure 3(d) shows essential PC3D elements which were located on the nodal position of constructed dummy solid elements. By using this method, we could handle proper hoop boundary condition at PC3D elements to hold wedge shape. Of course, Abaqus has the methodology that can convert from Lagrangian finite elements to SPH particles. But this conversion technique was not easy to manage appropriate local boundary conditions on the elements on the symmetric face, because SPH is only available with GENERAL CONTACT and the large number of PC3D elements was unnecessary generated.



(a) (b) (c) (d)

Figure 3: (a) ALE Modeling; (b) CEL Modeling; (c) dummy SPH Model; (d) Essential SPH Modeling

3 RESULTS

3.1 Results

Figure 4 shows the force-displacement responses of the punch for all analyses. The legend is analysis method plus the number of hardness of SPFC. The results of CEL were the largest in three methods among all SPFC materials, while the results of ALE were the smallest.

All deformation plots are shown in Figure 5 to 7. Figures of left column show the contour plots of Mises stress, the other right column figures show the result of Equivalent plastic strain. As the hardness of upper sheet became higher, the axial distortion of the rivet grew large and the rivet was not flared naturally as shown in Figure 7. While the rivet was flared in two sheets and this deformation caused interlock in case of SPFC440 as of Figure 5 (g) (h). These analysis results were not too far from the truth. In addition, deformation figures indicated that PC3D elements on the symmetry boundary area held the fixed condition of the hoop direction by our modeling method.

Although ALE revealed clear deformation shape of each sheets due to adaptive meshing function, it could not analyze completely in all SPFC specimens because of the element distortion at the center area on aluminum lower sheet (see Figure (a) (b)). And it could not be seen the separation of upper sheet in ALE method.

Similarly, CEL could not express a separation state as shown in Figure (c), and it took tremendous CPU time as shown in Table 1 in the next section 3.2. Furthermore, the lower sheet suffered severe distortion without adaptive meshing.

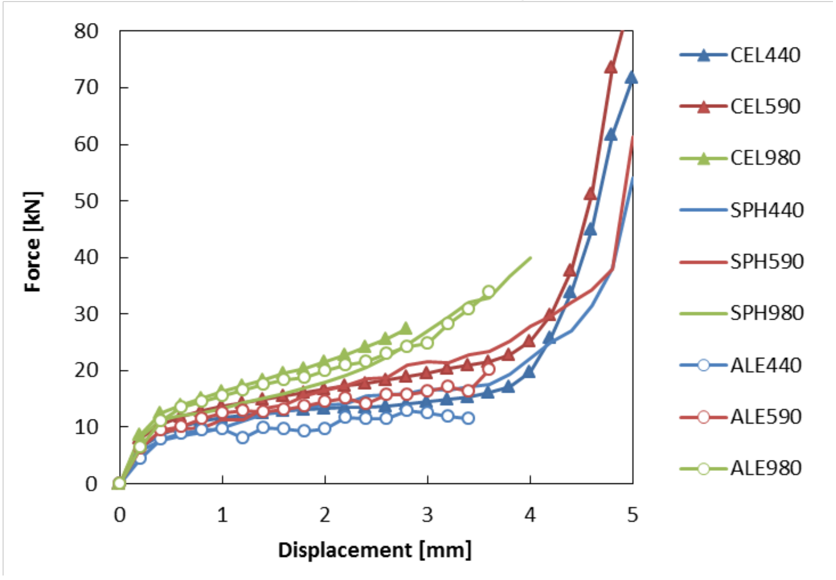


Figure 4: Punch force versus displacement

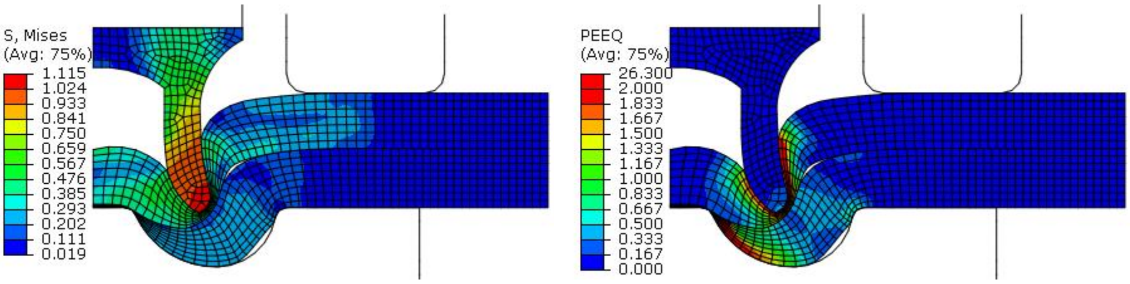
3.2 Analysis Time

Table 1 shows the analysis time (wallclock time [hh:mm] in the Abaqus log file) with parallel processing under Windows 7 64 bit operating system and a computer having two Intel Xeon E5-2620 (2.10GHz processor six cores). All jobs were analyzed under 12 cores parallel processing with Abaqus version 6.14-5.

Note that all analyses in ALE were not executed completely, and CEL for SPFC980 also ended at 58% of the total phenomenon time.

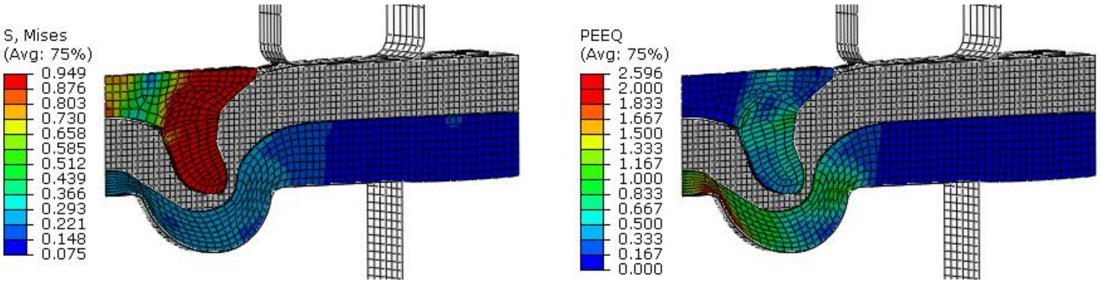
Table 1: Analysis time

Material for upper sheet	Wall clock time [hh:mm]		
	ALE	CEL	SPH
SPFC440	00:04	12:24	00:17
SPFC580	00:04	12:38	00:17
SPFC980	00:04	8:06	00:15



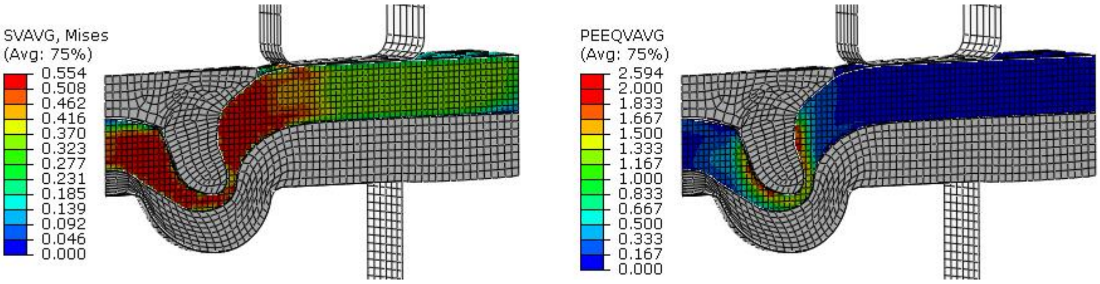
(a) Mises stress (ALE)

(b) Plastic strain (ALE)



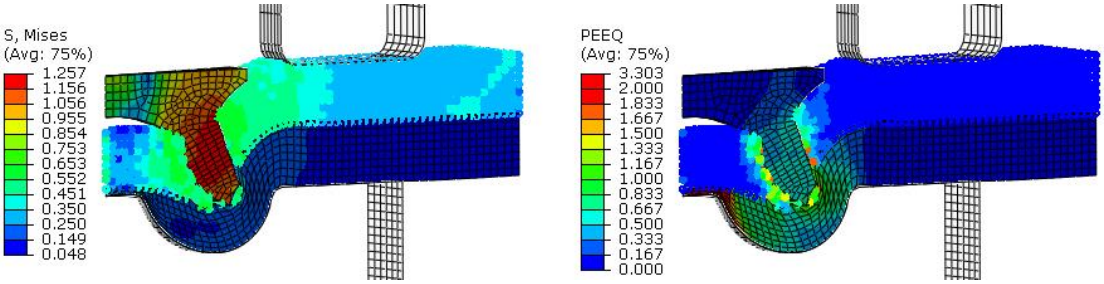
(c) Mises stress (CEL)

(d) Plastic strain (CEL)



(e) Mises average (CEL)

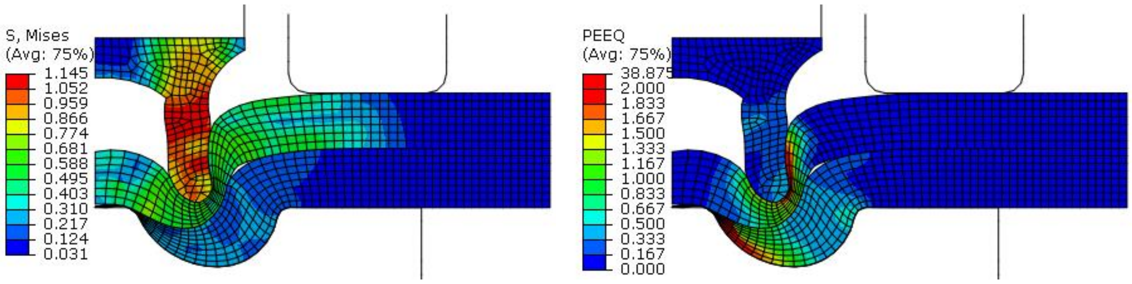
(f) Plastic strain average (CEL)



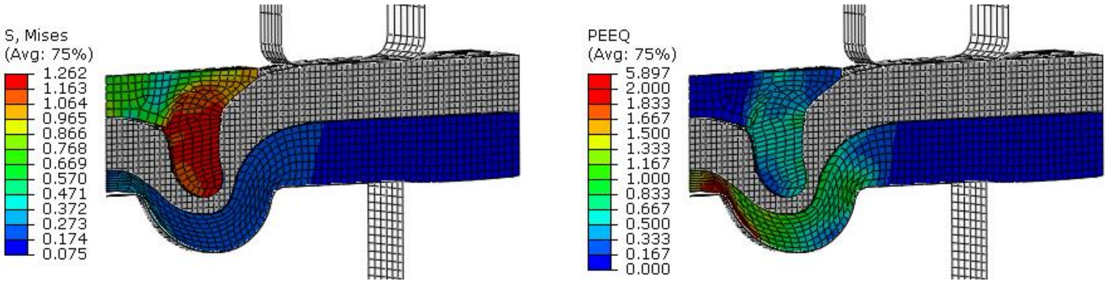
(g) Mises stress (SPH)

(h) Plastic strain (SPH)

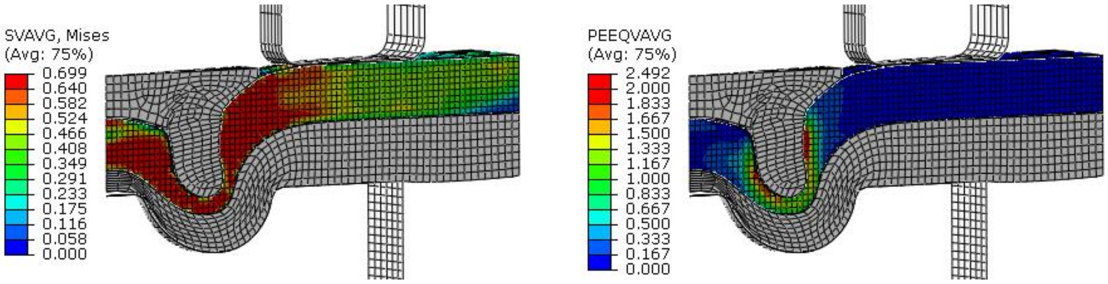
Figure 5: Results of SPFC440



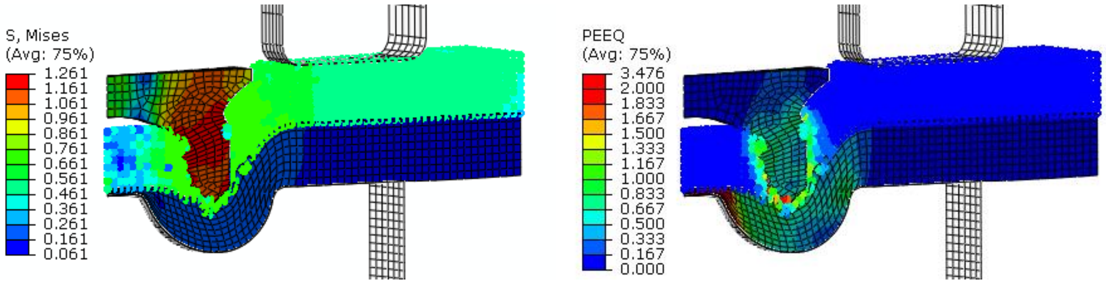
(a) Mises stress (ALE) (b) Plastic strain (ALE)



(c) Mises stress (CEL) (d) Plastic strain (CEL)

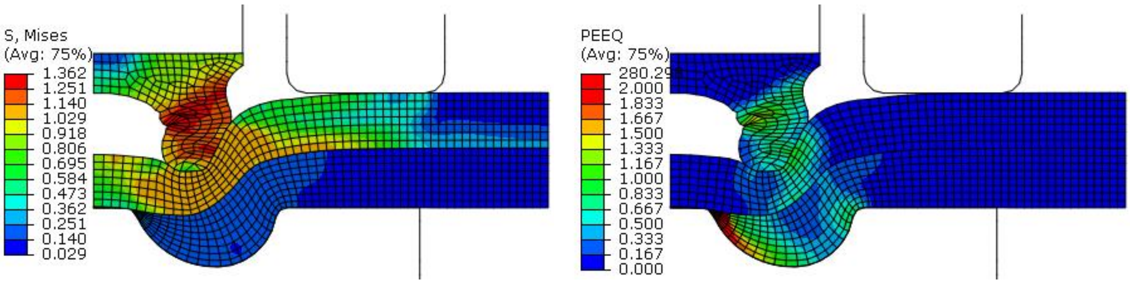


(e) Mises average (CEL) (f) Plastic strain average (CEL)

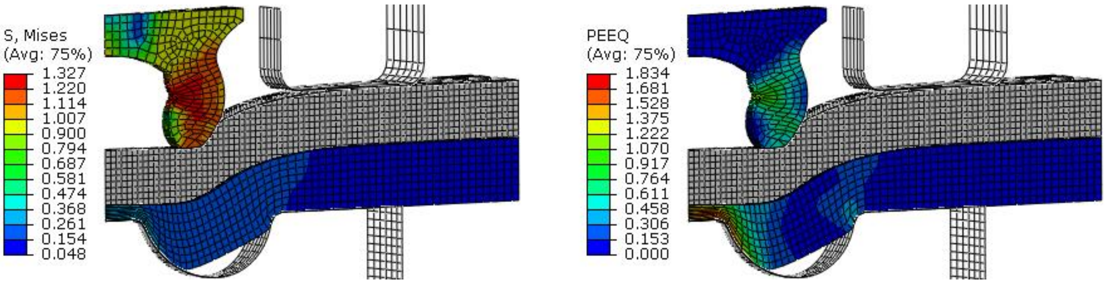


(g) Mises stress (SPH) (h) Plastic strain (SPH)

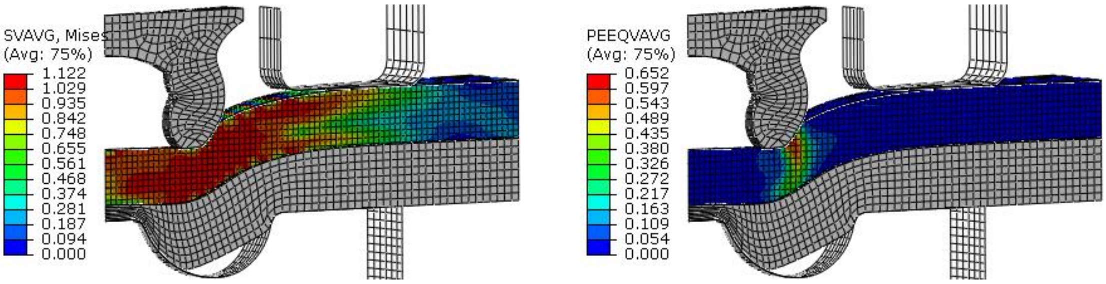
Figure 6: Results of SPFC590



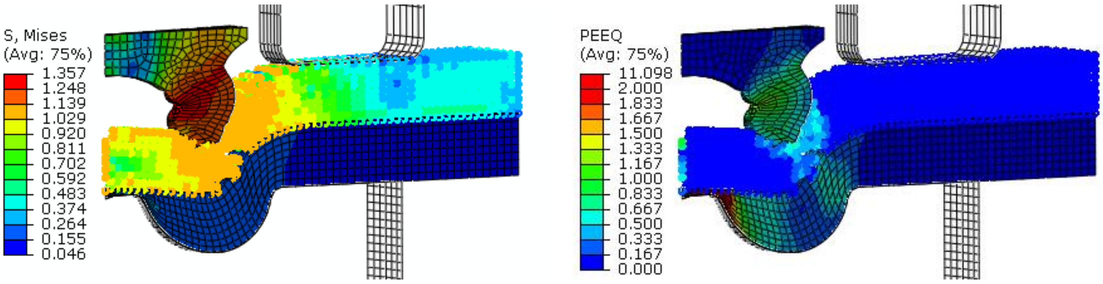
(a) Mises stress (ALE) (b) Plastic strain (ALE)



(c) Mises stress (CEL) (d) Plastic strain (CEL)



(e) Mises average (CEL) (f) Plastic strain average (CEL)



(g) Mises stress (SPH) (h) Plastic strain (SPH)

Figure 7: Results of SPFC980

4 DISCUSSION

The focus of our research was to develop the analysis methodology to simulate the SPR forming process. To accomplish our objective we investigated the use of Abaqus/Explicit techniques which avoid the problem of large distortion of element and allow us to enter a new regime. This investigation provided the following important findings.

4.1 ALE

Nodes were relocated to proper position in accordance with deformation in ALE analysis by virtue of adaptive meshing. Since ALE cannot treat damage material, we were not able to see the rivet penetration to upper sheet. But this method is effective even in axisymmetric dimension and is easy to use with low cost. Thus we are able to achieve brief result for SPR process with various materials, die shapes and speeds. In another word, this method is effective to acquire optimal shape design with like Tosca structure.

4.2 CEL

Figure 8 indicated that each analysis method for each SPFC materials showed the same tendency of punch force. However the final forces of CEL were much larger than those of SPH. For instance, the total force of CEL440 was 71.9kN, while SPH440 was 54.1kN. This difference might cause from residual material around the top of rivet in CEL methods.

It was able to find the piercing of rivet in mild SPFC 440 or 590, also the analyses were completely done except hard material SPFC980. On the other hand, this method required enormous CPU time.

4.2 SPH

The rivet could penetrate the upper sheet as shown in Figure 9 (g) (h) for material of SPFC440. This SPH deformation was quite similar to Figure 1 which was a condition almost same as our numerical experiment. This similarity showed that our methodology was appropriate. But our testing condition showed a tendency of no penetration at lower sheet, because we neglected the damage on the lower sheet in this study. If we assume the state of the both sheets rupture, it is necessary to take different technique. Now we cannot use SPH and ALE together, therefore the hybrid method is expected.

SPH method provides insight into the forming mechanism of SPR; moreover the analysis wall time was much less than CEL methods. However it required special care to define the PC3D element for the sake of structure, position and density. For this reason, we developed the way of constructing PC3D elements from nodes composing normal hex diagonal solid elements. We found that our SPH modeling was effective for symmetric condition and we were able to manage particle behavior on the wedge faces for axisymmetric structure such as SPR with few CPU time.

5 CONCLUSION

In conclusion, we examined three methods of Abaqus/Explicit for SPR forming simulation. To acquire the appropriate deformation especially for penetration, we found that SPH method was remarkable way for SPR forming. However, we did not compare analysis and experiment results, therefore we need moreover study including comparison with experiment. As a future work, we have to compare analysis and experimental results. For this purpose, we are trying to do experiment for various shapes and materials, and we will present comparative study in the near future.

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