

Experimental and numerical analysis on bilayer tube forming

J M Olevnik¹ and C P Nikhare^{1*}

¹ Mechanical Engineering, The Pennsylvania State University, Erie, PA-16563, USA

* E-mail: cpn10@psu.edu

Abstract: Moving deeper into the twenty-first century, lightweight construction has become a central principle in component design in industry-wide efforts towards increasing vehicle fuel economy to maintain adherence to tighter government environmental standards. To achieve new levels of weight reduction in components, simplistic materials are being replaced with compound materials and composites such as tailored blanks and multi-layered materials or 'hybrid' components when dissimilar materials are used together (metal and plastic polymer, for example). Usage of these new composite materials has been observed to yield lower component weights as well as the same or higher performance as conventional materials. To investigate this further, conical flaring of a hybrid, bilayer tube comprising an interior metal tube surrounded by an exterior polymer tube is considered. For experimentation, a steel inner tube was used with a PVC exterior tube. In testing, the formability of the steel tube was observed to have increased with the implementation of the exterior PVC layer in comparison to single layer tubes comprised of steel alone. Observation and analysis of this behavior pointed towards the contact stress of the two materials increasing the formability and delaying the failure. Beyond the scope of observing the flare, another property of the bilayer tube was that the addition of the PVC layer reduced the collapse of the steel tube adjacent to the flared region, which remained undeformed. The results of experimentation confirm that the hybrid component outperforms its conventional counterpart by exhibiting higher formability, lower stress in the flared region, and better overall structural integrity of the specimens after being flared.

1. Introduction

Metal forming is a major process in the manufacturing industry where part production is reaching quantities of hundreds of thousands and beyond. These industries typically cater to the automotive and aerospace industries which demand large quantities of parts in assembly. These parts, being metal, all add up to considerable amount of weight for a fully assembled vehicle of sorts. In these industries, weight is directly related to fuel economy where in the automotive sector, a 3.3% improvement in fuel economy is achieved with a 10% reduction in overall weight [1]. On top of this, governments are continuously imposing more stringent regulations on emissions and fuel consumption taxes that effect manufacturers as well as consumers. Advancements in weight reducing technologies are in demand to reach higher fuel economy in vehicles.

To achieve lighter parts and reduce weight, the reduction of material usage per part is examined. Reducing the amount of material used in the part does reduce weight but also reduces cross-sectional area which is normally a detriment to strength. To overcome the problem of a higher stress, a material of higher strength with a reduced gage area and weight is required, so the usage of composite materials



is examined. Composite materials implement the usage of dissimilar materials such as a metallic or ceramic component and a polymer component to obtain a product with equal or greater performance than a single component product [2].

One way to approach this is to consider using a bilayer material. These products are commonly found in tubular form therefore a bilayer tube is considered for analysis. Bilayer material products are already being utilized for their resistance to corrosion [3] and are also exhibiting characteristics of greater strength than single layer materials. Bilayer tubes have already been found to exhibit higher shear strengths than a product of a single material and can tolerate radial and axial deformation [4]. The tolerance to deformation is critical to construct form fitted joints for tubes through flare fitting. Form fitted joints are typically applied where tubes are being used to transfer fluids (e.g. hydraulic lines, fuel gas lines, water lines, etc.) where permanent joints formed by soldering or brazing would be impractical and a mechanical joint is desired. Moreover, these types of joints have become standardized in SAE (Society of Automotive Engineers) and NFPA (National Fire Protection Association) codes [5]. These bilayer products are manufactured through mechanical or metallurgical methods. Common mechanical and metallurgical methods are extrusion, hydroforming [6-8], compression [9], explosive bonding [4, 10], centrifugal casting [11], diffusion bonding [12], roll bonding [13-14], laser cladding [15], etc. Bilayer products are mostly popular with tubular components. As mentioned, bilayer tubular components can be a primary process, and then secondary operations are performed by using hydroforming, compression or tube flaring. These operations are typically performed to make a form fit joint. The general method for tube forming is carried out by cross-section expansion, reduction and bending or expansion by means of fluid pressure or a solid mandrel. Such formed tubes are used for fluid flow (e.g. exhaust, heat exchanger etc.) or in support frames for engineering structures [16]. Tube flaring is one of the classifications of tube forming processes. In tube flaring, the tube is expanded to shape by pressing a conical mandrel into the tube end and continuing down the length of the tube to a desired displacement. There are variations between flare angles that depend on codes and standards in context to how the flare will be applied. For single layer tube forming, there is a great amount of literature available, but there is a very limited amount of literature on the subject of bilayer tube forming. In this paper, forming of a bilayer tube flare was performed experimentally in physical tests and was modeled for numerical analysis, simulated, and compared. For this, the bilayer tube was constructed by inserting the metallic tube in to a polymer tube. The force required for flaring and failure was examined in physical tests and comparison was made with numerical simulations. Further, the contact pressure/stresses were studied through numerical analysis and found it helps in delaying the failure.

2. Material and Methodology

To explore bilayer tubing in physical testing, metal-polymer bilayer tubes had to be custom fabricated. For these tubes, the materials of choice were a low-carbon steel tube and Schedule 80 Polyvinyl Chloride (PVC) plastic polymer conduit pipe for the interior and exterior tube, respectively. PVC was selected because it is easily sourced, but also because it was of a different strength than steel and of lower elastic stiffness. The steel tube had an outside diameter of 38.1 mm (1.5 in) and this dimension was shared with the inside diameter of the PVC tube. The close tolerance allowed the tubes to be joined through a mechanical bond such that any testing factors from an adhesive layer could be neglected. The received thickness for steel and PVC tube was 1.25 mm (0.05 in) and 5.14 mm (0.2 in), respectively. The PVC tubes were 88.9 mm (3.5 in) in length and the steel tubes were 92 mm (3.625 in). Proof-of-concept tests showed that with equal length tubes, the interior steel to shifted inside the PVC tube upon flaring expansion and yielded undesirable results. The addition of 3.175 mm (0.125 in) on the steel tube eliminated the shift.

Experimentation started with finding the properties of the materials under investigation. Tensile tests were performed using an MTS 810 Material Test System and an MTS Laser Extensometer to determine the elastic modulus and ultimate strength. Figure 1 shows a basic schematic of the tensile testing setup. Tensile specimens were fabricated from cutouts taken from untouched sections of tubes

used in flare testing. Loading force was recorded as the top grip was displaced upward. The laser extensometer provided change in length data which shines parallel to the tensile specimen and hits the two pieces of reflective tape where the distance between the reflection points are recorded for tensile stress-strain curve calculation.

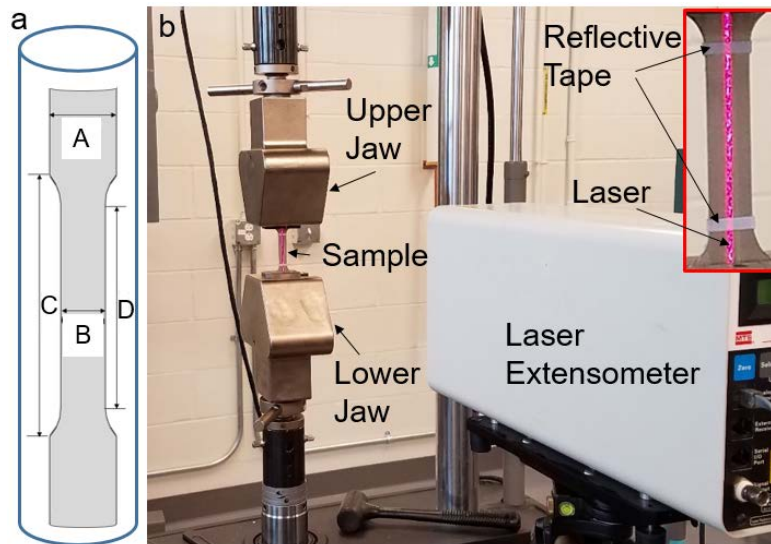


Figure 1. Tensile test experimental setup (Specimen dimensions: A = 9.5 mm; B = 6.35 mm; C = 38.1 mm; and D = 29.7 mm) [17].

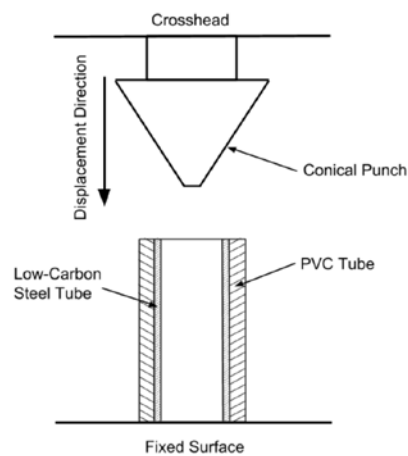


Figure 2. Tube flaring experimental setup.

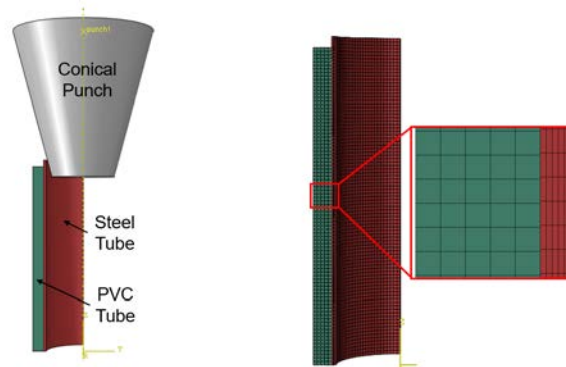


Figure 3. Numerical analysis setup and object mesh with detail.

For each material, flare tests were performed on the steel tubes and PVC tubes individually. Tests were performed on a Tinius-Olsen 120-kip testing machine. The general setup for the tests can be seen in Figure 2. The conical punch with a cone angle of 30° was used for flaring process. The punch was made of D2 steel with a 58C Rockwell hardness after quench and tempered. The punch was mounted to the crosshead and was displaced into the tube at 25 mm/min until the punch reached full depth into the tube or until failure of the tube. In single layer testing, the steel and PVC were the same dimensions as they would be in a bilayer construction. The tubes were flared to examine performance. A thin layer of WD-40 lubrication was utilized between tool and tube. Three single layer tests in total were performed for each material. Once the behavior of the steel and PVC tubes were examined independently, bilayer specimens were assembled and flared in the same manner as single layer tests.

Numerical analysis of single and bilayer tube flaring was performed using the ABAQUS/Explicit finite element code (version 6.13-2). Figure 3 shows the model set-up for tube flaring numerical analysis. Only the quarter of the full geometry was used in simulation to reduce the computational time as can be seen in Figure 3. The conical punch was set as a rigid body and the tube a deformable body. C3D8R solid brick elements were used to mesh the tubes. 5 elements through the thickness of each tube was used to capture the bending effect (Figure 3). No mass scaling was utilized in numerical model. The bottom edges were kept free in all degrees of freedom except in the downward direction to allow for any possible radial expansion or contraction. No friction condition was utilized as the tube was flared only on top part. The locking of the bottom edge also kept the tubes together relative to each other as if they were flared on a solid surface. The boundary between the interior of the steel tube and the punch was defined as tangential contact between the surfaces. Multiple coefficients of friction for contact between the punch and steel tube and between steel tube and PVC tube were analyzed. The friction coefficient for best fit with experimental force displacement curves was selected for further analysis. Displacement control method was used to deform the tube as it was set for experiments. The data collected from the numerical approach was used to verify the similarity to the physical tests using force-displacement curves. Such confirmation allowed the use of the numerical analysis predictions for the stresses, strains, and contact pressure/stresses to give a relative approximation on quantities, which would be difficult to record in experiments.

3. Results and Discussion

The engineering stress-strain curves from the tensile tests are shown in Figure 4. It can be seen that the steel exhibits a higher elastic modulus than the PVC (refer Table 1). The PVC exhibited a longer plastic region and therefore higher ductility than the steel. For numerical analysis, the engineering stress and strain was converted to true stress and strain which can be seen in Figure 5. Due to the nature of the PVC stress strain curve, the power law was not the best-fit equation and thus a direct material raw data was used. This approach provided mechanical properties to be used in simulation with isotropic hardening (Table 1).

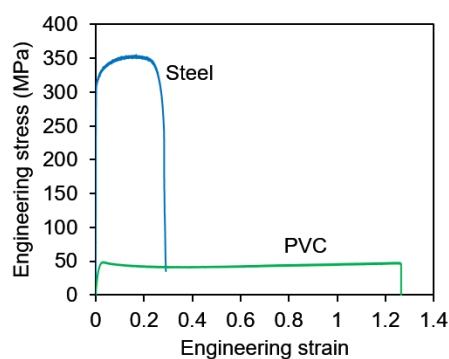


Figure 4. Steel and PVC engineering stress-strain curve.

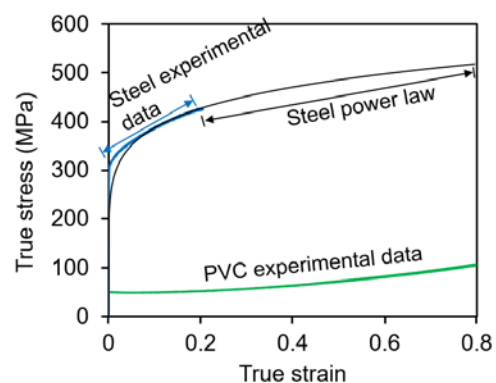
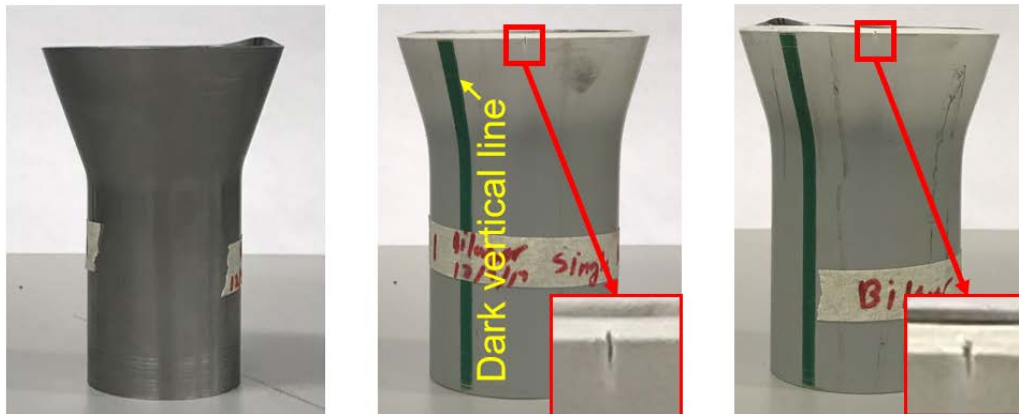
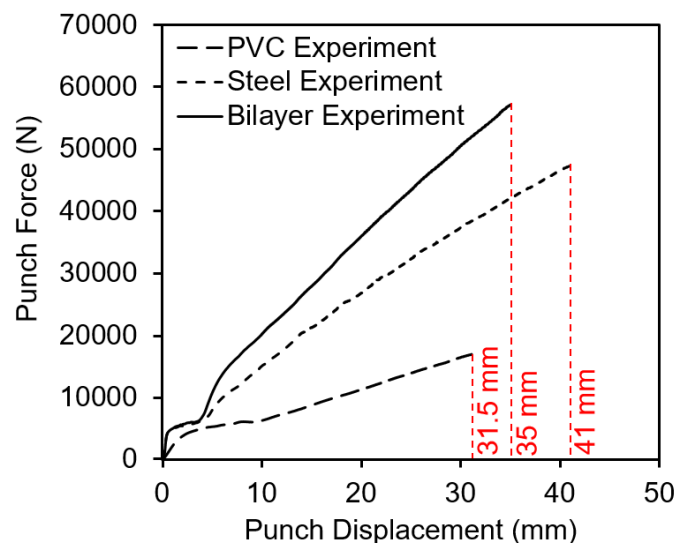


Figure 5. Stress-strain curves for numerical simulation with power law curve.

Table 1. Mechanical properties of low carbon steel and PVC tubes

Material	Density (kg/m ³)	Elastic Modulus (MPa)	Yield strength (MPa)	Strength coefficient "K" (MPa)	Strain hardening exponent "n"
Steel	7800	210000	307	535	0.14
PVC	1380	3314	50	--	--

**Figure 6.** Experimental deformed tubes; left: single layer steel, middle: single layer PVC, right: bilayer tube. Red circle indicates crack.**Figure 7.** Experimental force-displacement curve for single layer PVC and steel tubes and bilayer tube.

Experimental flaring tests were successfully performed to the full depth of the punch. Small cracks appeared on the top edge of the single layer PVC as well as on the PVC layer of the bilayer tube as shown in Figure 6. No catastrophic failures occurred and the cracks highlighted in Figure 6 were the only ones to develop. One notable observation is the location of the crack. It appears approximately at same location from the dark vertical line on the PVC tube (Figure 6). This means the tube is weaker in this region and it may be due to how the tube was extruded. Figures 7 provide the force-displacement curves for single layer steel, single layer PVC and bilayer flaring tests which were performed to either failure of the sample or until the punch tool reached full depth into the tube. In the experiments, steel tests were performed until full depth with no observed failure, while the PVC tests all catastrophically failed at the point of full depth of the punch into the tube. Comparing force-displacement curves, the

steel tube was able to absorb ~270% more energy than the PVC tube. Contrary to hypothesized results, the peak punch force in the bilayer was less than the summation of the individual layer tests by ~9% (Figure 7).

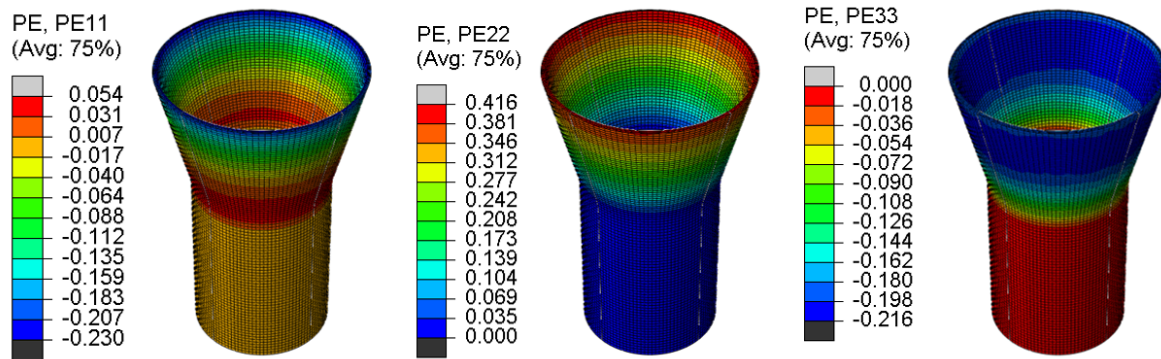


Figure 8. Predicted plastic strain contour for single layer steel flaring; left: thickness strain, middle: circumferential strain, and right: axial strain.

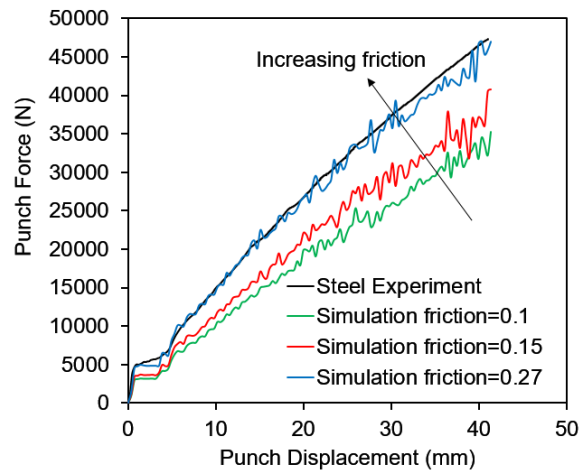


Figure 9. Steel flare numerical result force-displacement curves per simulation friction with experimental curve.

Figure 8 provides the predicted plastic strain contours for thickness, circumferential, and axial strain for single layer steel flaring. The thickness strain plot shows a negative strain on the top edge of the flare which indicates a reduction in the thickness of the steel compared to the gage thickness. The strain decreases in magnitude down the flare as the thickness increases and the deformed-undeformed region displays a positive result indicating an increased thickness of the steel. The circumferential strain plot displays a maximum strain at the top edge of the flare where there is the most tensile deformation and gradually decreases down the flare to the undeformed region. The axial strain plot displays a negative strain which indicates compression which stays constant down the length of the flared region and reduces through the deformed-undeformed transition. Note that there is very little axial strain occurring in the undeformed region which suggests a majority of the energy is absorbed in the flare.

Figure 9 shows the predicted force-displacement result for single layer steel flare. Multiple simulations were run, each with the different friction coefficient representing contact between the tube and punch. It can be observed that the frictional coefficient of 0.27 yielded the closest match to the measured steel force-displacement curve.

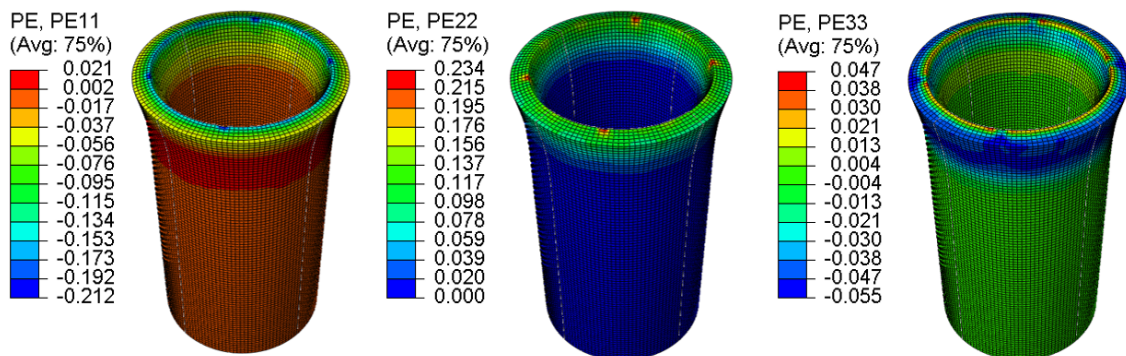


Figure 10. Numerical plastic strain contour for single layer PVC flaring; left: thickness strain, middle: circumferential strain, and right: axial strain.

Figure 10 provides the numerical plastic strain contours for thickness, circumferential, and axial strain components for single layer PVC flaring. It can be observed that the highest localized strain occurred at the center of quarter tube (circumferential strain PE22), which indicates the similar crack initiation in experiments (Figure 6). Figure 11 shows the predicted force-displacement result for a single layer PVC flare. Just as with the steel flares, multiple simulations were run with different friction coefficients. The frictional coefficient of 0.18 yielded the closest match to the experimental PVC force-displacement curve.

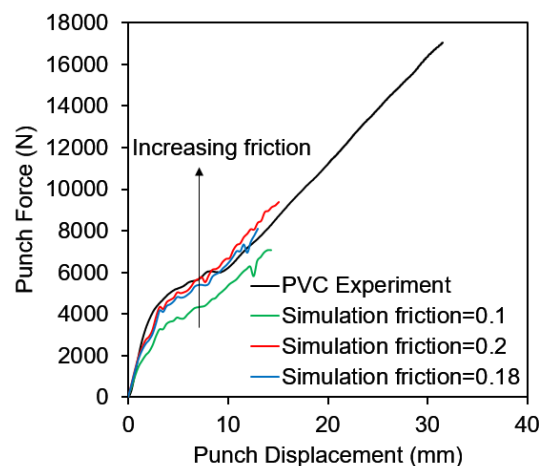


Figure 11. PVC flare numerical result force-displacement curves per simulation friction with experimental curve.

Figure 12 provides the predicted plastic strain contours for thickness, circumferential, and axial strain for bilayer flaring. The results from the bilayer numerical simulation show more activity in the external PVC layer. The behavior of the PVC is comparable to that of the single layer steel (Figure 9) with similar deformation patterns for thickness, circumferential, and axial strain. For the equivalent strain, there are areas of strain between the Steel and PVC with no observable strain occurring on the surfaces of the bilayer. Equivalent stress displays a maximum on the steel tube in the flared region with very little stress being transferred into the PVC (Figure 13). The bilayer numerical force-displacement result is shown in Figure 14. The curve includes the experimentally matched friction coefficients and fits the path of the experimental bilayer curve very closely.

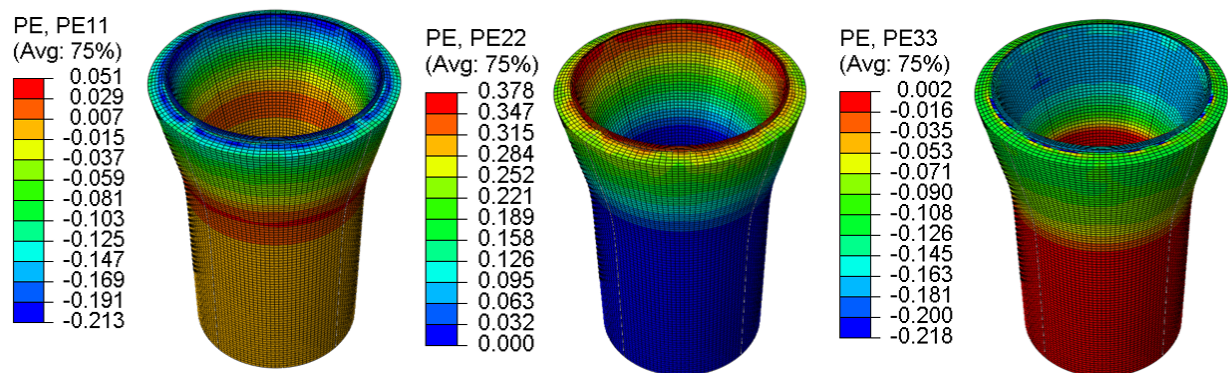


Figure 12. Numerical plastic strain contour for bilayer flaring; left: thickness strain, middle: circumferential strain, and right: axial strain.

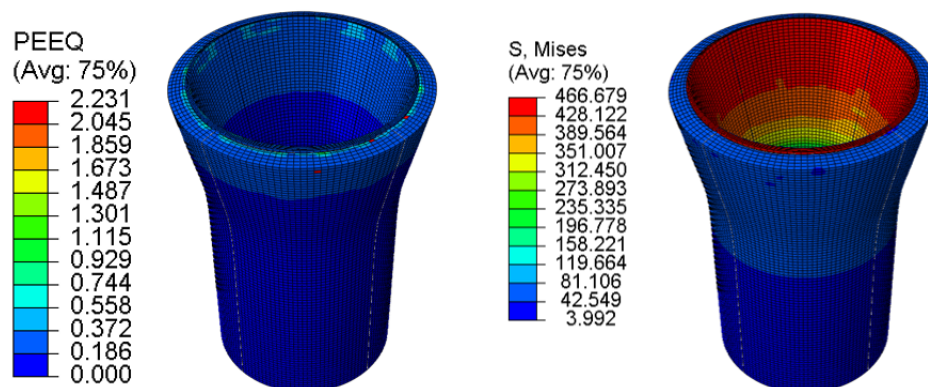


Figure 13. Numerical equivalent plastic strain (left) and stress (right) contour for bilayer flaring.

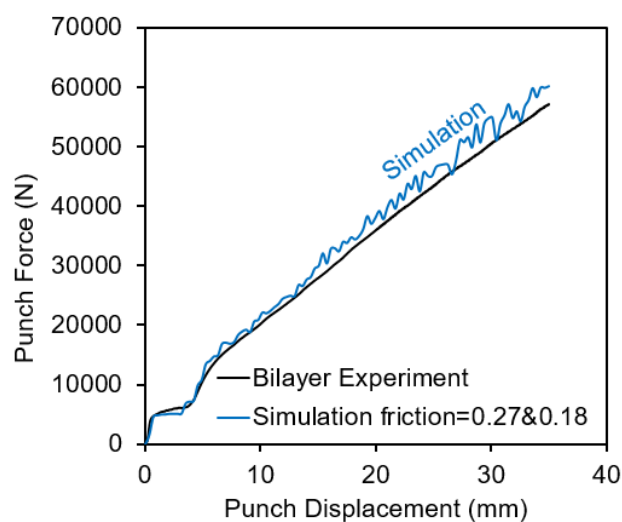


Figure 14. Numerical and experimental force displacement comparison for bilayer flaring.

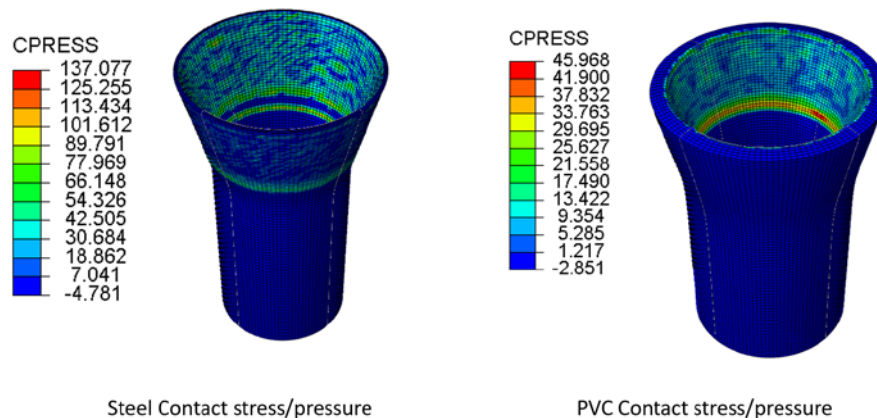


Figure 15. Numerical contact pressure/stress in steel and PVC tube during bilayer flaring.

The contact stress map between the tubes in the bilayer simulation is shown in Figure 15. The steel contact stress contour on the steel layer shows a rippled pattern of contact stresses on the interior of the flared region between the punch tool and the tube while on the exterior of the flare between the Steel and PVC, there is a minimal amount of contact stress. There is a thin ring of no-contact just above the deformed-undeformed transition. This is due to bending of the material during flaring. Below that is the point of initial contact with the punch where there are small areas of peak contact stress. Looking at the PVC layer, the same rippled pattern of contact stress exists on the interior of the flared region, but as mentioned previously there is a minimal stress on the outside of the steel. This can be attributed to the steel applying stress to the lower strength PVC. Unlike the steel, there is no ring of no-contact just above the deformed-undeformed transition, but there is a larger, more defined ring of peak contact stress.

4. Conclusion

In this paper, bilayer tube flaring was investigated through simulation in numerical analysis and through physical experimentation. Low-carbon steel and PVC tube were used to construct the bilayer tube with the steel tube on the inside and the lower elasticity PVC on the outside. Initial tensile tests of material samples showed that the PVC exhibited much lower strength and higher ductility in longitudinal direction than the steel, but early failure seen in circumferential direction. In the single layer flaring experiments, the steel displayed no signs of failure while the PVC failed in every test. For the steel-PVC bilayer flare experiments, there were no failures to either layer. The PVC layer did show small tears in the top edge of the flare, but did not result in a catastrophic failure. This shows that the contact between the two tubes kept the PVC layer together and halted failure. For the numerical analysis, force-displacement curves from simulation matched the experimental curves well with the right frictional coefficient. With adequate friction coefficients for both contact surfaces, the bilayer numerical result compared very well to the experimental curve and allowed the use of other numerical results such as stress and strain predictions. The desired numerical result was the contact stresses between the tubes of the bilayer. The results showed contact stress on the inside of the PVC but not on outside of the steel. It can be concluded that the contact stress is a result of the steel being pressed into the PVC. This is what is keeping the outside PVC layer together proving an increase in formability and delay of failure with the implementation of the bilayer.

Acknowledgements

The authors would like to acknowledge Penn State Behrend for providing the facilities to conduct the experiments, the Penn State Undergraduate Research Grant for funding, and thanks to technician Glenn Craig for the fabrication of test samples.

References

- [1] Casadei A, and Broda R 2007 *www.autoaluminum.org*
- [2] Gay D 2014 *Composite materials: design and applications*. CRC press.
- [3] Liu F, Zheng J, Xu P, Xu M, and Zhu G 2004 *International Journal of Pressure Vessels and Piping* **81(7)** 625
- [4] Sun X J, Jie T A O, and Guo X Z 2011 *Transactions of Nonferrous Metals Society of China* **21(10)** 2175
- [5] Copper Tube Handbook. Copper Development Association. 43
- [6] Mori K I, Bay N, Fratini L, Micari F, and Tekkaya A E 2013 *CIRP Annals* **62(2)** 673
- [7] Wang X, Li P, and Wang R 2005 *International Journal of Machine Tools and Manufacture* **45(4-5)** 373
- [8] Spence M A, Roscoe C V, Schafer K, Hutchison J, Foxton A, and Barraclough C 1999 *Oil and Gas Journal* **97(18)** 80
- [9] Nikhare C 2015 *Proc. of IDDRG2015*, Shanghai, China
- [10] Kahraman N, Gülenç B, and Findik F 2005 *Journal of Materials Processing Technology* **169(2)** 127
- [11] Sponseller D L, Timmons G A, and Bakker W T 1998 *Journal of materials engineering and performance* **7(2)** 227
- [12] Bhanumurthy K, Fotedar R K, Joyson D, Kale G B, Pappachan A L, Grover A K, and Krishnan J 2006 *Materials Science and Technology* **22(3)** 321
- [13] Kim S H, Kim H W, Euh K, Kang J H, and Cho J H 2012 *Materials & Design* **35** 290
- [14] Li X, Zu G, and Deng Q 2011 *Light Metals* 615
- [15] Ocelík V, and De Hosson J T M 2010 *Advances in Laser Materials Processing*
- [16] Nikhare C 2012 *Proc. of IDDRG*, Mumbai
- [17] Pier B, Nikhare C 2018 *Proc. of the ASME 2018 International Manufacturing Science and Engineering Conference* (accepted)