Bimetallic Axle Preform Development for Heavy Duty Truck Weight Reduction

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Abstract

Heavy duty vehicle manufacturers face continuous demands to improve vehicle performance and fuel economy. Reducing gross vehicle weight is a key strategy for achieving both of these aims and is primarily accomplished by reducing the weight of individual components. Heavy duty truck axles, which are presently formed from solid steel billets, represent potential candidates for weight reduction. Due to the stress field generated while in service, these monolithic axles can potentially be lightened by using an aluminum alloy in low stress regions while retaining steel alloys for usage in higher stress regions. To achieve components having “dual” metal construction will require the use of bimetallic assemblies which consist of an outer steel shell and an inner aluminum core. Such bimetal assemblies will also necessitate the use of new manufacturing procedures. This study utilized finite element models to evaluate selected manufacturing processes with the goal of determining which of these had the best potential for producing a bimetallic axle geometry. Processes based on both frictional and mechanical contact were considered and the results indicate that radial forging and forward extrusion would be the most practical and cost effective. Further study is recommended to optimize each process and subsequently attempt to manufacture prototype axle preforms by each approach. Once the experimental preforms have been thoroughly evaluated and the manufacturing process is optimized, manufacturers can begin mass producing bimetallic axles to reduce vehicle weight.
Chapter 1
Introduction and Overview

1.1 – Basis for Weight Reduction in Heavy Duty Trucks

Commercial heavy duty truck manufacturers are under continuous regulatory and customer demands to improve vehicle performance and fuel economy [2]. Reducing vehicle weight represents a critical means for meeting these demands but also places pressure on OEMs to accomplish this without sacrificing quality. Solid steel components are of particular interest due to steel’s relatively high density compared to other engineering materials. Heavy duty truck torque transmission axles and shafts are currently forged and subsequently machined from solid billets of either AISI 4140 or AISI 3310 steel grades. Monolithic steel axles perform satisfactorily, but due to the varying stress field during service, a significant portion of the cross-section bears little load. The Marquette University study is part of a larger technical project sponsored by the FIERF Forging Foundation to investigate the feasibility of redesigning the current axles to reduce weight while retaining sufficient strength and rigidity to meet performance requirements.

1.2 – Reference Study

Previous work done at North Carolina State University [4, 5] proposed that one possibility for reducing axle weight while maintaining current performance levels is to employ a bimetallic axle. According to the NC State study, the use of bimetallic axles could potentially reduce the weight of a truck by 16 - 19.2 kg and offers the largest weight saving means in heavy duty trucks compared to other components such as gearbox input and output shafts and countershafts. In a bimetallic axle, the core is formed from a lightweight metal such as aluminum and housed within a steel shell. During torque transmission, the greatest shear stresses occur near the outside of the axle and steel is sufficiently strong to withstand the stress levels and remain in the elastic region. However, stresses tend to decrease toward the center of the axle such that a lighter, lower strength material is sufficient to withstand the reduced stress levels.
The study completed by NC State explored the idea of hot-warm forging to create the bimetallic axle. A hybrid hot-warm forming process was needed due to the large disparity in working temperatures between the two alloys. In that study, the preform, encompassing both the steel shell and aluminum core, was heated to 400°C and formed accordingly. However, as noted in the study, hot-warm forging does not create a strong bond between the two materials and the resulting axle may not be corrosion resistant.

1.3 – Study Objectives and Preform Design Parameters

Though the potential for achieving weight savings with a bimetallic axle is made evident by the NC State study, manufacturing a bimetallic axle is not trivial. As axle forging was considered in the NC State study, the objective of this study was to propose and evaluate the feasibility of manufacturing a bimetallic aluminum-steel blank via several different processes and identify potential technical challenges inherent to each. The feasibility analysis was performed using DEFORM™ finite element simulation software to model each candidate process. Based on the results, the most promising preforming processes will also be identified.

Representative axle dimensions and materials were chosen based on data provided in previous NC State reports [4, 5] and are presented in Table 1.1. All but one candidate preforming process considered in this study requires a preformed aluminum core to be inserted into a preformed steel shell prior to the forming operation. Practical assembly practice necessitates that some amount of radial clearance must exist between the core and shell to facilitate assembly. In this study, the minimum acceptable radial clearance was considered to be 0.075 mm (0.003 in). This clearance was included in simulations whenever possible, but was omitted from several simulations due to convergence problems in the FE model.

**Table 1.1 – Representative Axle Parameters Chosen for Feasibility Study**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Chosen Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Radius</td>
<td>12.5 mm</td>
</tr>
<tr>
<td>Shell Outside Radius</td>
<td>25 mm</td>
</tr>
<tr>
<td>Shaft Length</td>
<td>320 mm</td>
</tr>
<tr>
<td>Radial Clearance</td>
<td>0.075 mm</td>
</tr>
<tr>
<td>Core Material</td>
<td>6061-T6 Aluminum</td>
</tr>
<tr>
<td>Shell Material</td>
<td>AISI 4140 Steel</td>
</tr>
</tbody>
</table>
Dimensions listed in Table 1.1 are representative of the approximate diameter and length of heavy duty truck axles as well as the approximate diameter of a suitable core. Given this generalized geometry along with the fact a) steel’s density is 7.85 g/cc, and b) aluminum’s density is 2.7 g/cc, calculations made at NC State showed that axle weight could be reduced by 16% if the current design dimensions are retained. This geometry was chosen as a standard to compare the manufacturing processes evaluated in this study and identify which are likely to be the most effective. Optimizing those processes will be considered in a future study.

1.4 – Candidate Preforming Processes

For the bimetallic preform to function as an effective heavy duty truck axle, torque must be transferred between the core and shell without any slipping, i.e. no relative movement can occur between the core and shell interface surfaces. The two methods of achieving solid torque transfer (torque transferred without slipping) considered by this study were frictional contact and mechanical contact. Other preforming processes such as Solid-State Joining (SSJ), and Centrifugal Casting (CC) were also considered but were not pursued for the following reasons. On the surface, SSJ appears to be an ideal preforming process as it can form strong metallurgical bonds which would facilitate solid torque transmission. However, the interfacial bond formed by SSJ often lacks appreciable ductility such that fracture problems could arise during subsequent forming operations. In the case of CC, insufficient chemical compatibility between aluminum and steel could also lead to ductility problems. Moreover, the wall thickness of the steel shell in the current axle design was considered to be too thin for a bimetallic shaft based on current CC process capabilities. One other possible candidate for preforming might be shear flow forming. This idea was considered late in the study but could not be analyzed owing to the point contact conditions which necessitate development of a highly specialized simulation model.

Frictional contact interfaces do not suffer from low ductility because both materials retain their bulk properties at the interface and in both of the adjacent materials. Instead of bonding the two materials together, frictional contact relies on residual normal stresses being
present at the core-shell interface to generate frictional stresses. Such stresses result in elastic
deformation and prevent the interface surfaces from slipping past one another when torque is
applied. For the purposes of this study, a bimetallic preform was considered successful if
residual compressive normal stresses were present in both the core and shell in the vicinity of
the interface. On a simple cylindrical surface, normal stress and radial stress are equivalent.
Normal stress is zero at a free surface, so radial stresses that approached zero at the interface
represented a loss of contact and indicated the presence of a gap, i.e. an unsuccessful preform.
The manufacturing processes considered for generating frictional contact in this study for a
bimetallic preform were a) thermal shrink fitting, b) press fitting, c) radial forging, and d)
forward extrusion.

Mechanical contact relies on geometric interference between the core and shell to
transmit torque. Splines and shaft keys are examples of this geometry. The process considered
by this study used an extruded aluminum preform with integrated keys that fit inside of a steel
preform with matching slots. In order for the aluminum core and steel shell to be assembled,
some clearance must exist between the key and keyway on all sides. However, this clearance is
detrimental to the performance of the axle during torque transmission, especially when the
torque direction is reversed. As the torque is reversed, the core’s key will disengage from one
side of the shell’s keyway and subsequently make contact with the opposite side. This behavior
will cause significant damage over time. To prevent damage, the clearance gaps must be closed
after assembly by a forming process. This study considered a forward extrusion process similar
to the one used to generate frictional contact. The bimetallic preform was considered
successful if residual normal stresses existed at the core-shell interface along the cylindrical
surface and contact occurred along all three sides of the key and slot.

Rather than simulating the candidate forming processes for the full 320 mm length of
the axle, each was modeled and simulated until steady state conditions were established.
Models were considered to be at steady state once the cross sectional residual stress
distribution no longer varied significantly with axial position. Residual hoop and radial stress
distributions were recorded from the steady state regions and are presented in the appendices.
Chapter 2
Thermal Shrink Fit

2.1 – Process Description

Thermal shrink fit processes utilize thermal expansion and contraction to create a slip fit between two components while they are at different temperatures. The slip fit ensures that the components can be assembled with minimal effort. After assembly, the components are allowed to return to thermodynamic equilibrium and the temperature difference between them disappears. As this occurs, each component’s sizes changes such that the slip fit becomes an interference fit and the components are locked together. The relationship between dimensional change and temperature change in one dimensions is described by the well-known equation for thermal expansion:

\[ \delta = \alpha L (\Delta T) \]

Where:
\( \delta \) is the dimensional change
\( \alpha \) is the coefficient of thermal expansion
\( L \) is the initial length of a dimension
\( \Delta T \) is the change in temperature

2.2 – Simulation Model

The goal in any thermal shrink fit process is to create sufficient clearance for assembly at an initial temperature and a predictable amount of dimensional interference when the assembly returns to thermodynamic equilibrium. Dimensional interference results in elastic stresses which in turn generate frictional stresses that resist sliding between the surfaces. In order to accurately predict the thermal-dimensional behavior of the core and shell, temperature changes (heat-up/cool down) were simulated in each individual component prior to simulating assembly.
While heating causes expansion, it must be noted that excessive temperatures in the steel shell could potentially damage or melt the 6061 aluminum core. Consequently, it was decided to study the maximum clearance that could be gained by cooling the core first. The core was specified to have a radius of 12.500 mm at room temperature and cooling to two different temperatures was simulated using 2D axisymmetric elastic-plastic simulations. The simulated temperatures were chosen to represent dry ice (-78.5°C) and liquid nitrogen (-196°C) and the results are presented in Table 2.1.

Table 2.1 – Radius of the Isolated Aluminum Core at Several Temperatures

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Radius</th>
<th>Contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>12.500 mm</td>
<td>0.000 mm</td>
</tr>
<tr>
<td>-78.5°C</td>
<td>12.473 mm</td>
<td>0.027 mm</td>
</tr>
<tr>
<td>-196°C*</td>
<td>12.441 mm</td>
<td>0.059 mm</td>
</tr>
</tbody>
</table>

Core contraction at cryogenic temperature* was found to be insufficient to provide the entire 0.075 mm of radial clearance necessary for assembly. As cooling below this temperature becomes significantly more expensive, it was determined that some heating in the steel shell would also be necessary for the process to be economical. Several temperatures were simulated and the results are presented in Table 2.2.

Table 2.2 – Inside and Outside Radii of the Isolated Steel Shell at Several Temperatures

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Inside Radius</th>
<th>Outside Radius</th>
<th>Inside Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>12.500 mm</td>
<td>25.000 mm</td>
<td>0.000 mm</td>
</tr>
<tr>
<td>380°C</td>
<td>12.554 mm</td>
<td>25.108 mm</td>
<td>0.054 mm</td>
</tr>
<tr>
<td>400°C</td>
<td>12.557 mm</td>
<td>25.114 mm</td>
<td>0.057 mm</td>
</tr>
<tr>
<td>420°C</td>
<td>12.560 mm</td>
<td>25.120 mm</td>
<td>0.060 mm</td>
</tr>
<tr>
<td>500°C</td>
<td>12.572 mm</td>
<td>25.144 mm</td>
<td>0.072 mm</td>
</tr>
<tr>
<td>600°C</td>
<td>12.587 mm</td>
<td>25.174 mm</td>
<td>0.087 mm</td>
</tr>
</tbody>
</table>

According to these results, it is possible to gain the necessary clearance to assemble the bimetallic shaft by heating the steel shell above 500°C. However, the 6061 aluminum chosen for study exhibits a solidus melting transition at 582°C [3], so it was considered ideal to keep...
the shell’s temperature below 80% of this temperature (411°C) to preserve the core’s microstructure. In order to obtain the sufficient assembly clearance of 0.075 mm, it was decided to simulate the assembly with the aluminum core initially at -78.5°C and the steel shell initially at 400°C. Using this temperature combination resulted in a combined radial clearance of 0.084 mm when the surfaces were just touching at room temperature, allowing sufficient clearance for assembly and 0.009 mm of interference. To include this interference, the core was given an initial size identical to the results of the -78.5°C cooling simulation, while 0.009 mm was subtracted from the shell’s expanded size. All initial and final radial dimensions for the simulated assembly are presented in Table 2.3.

<table>
<thead>
<tr>
<th></th>
<th>Core Radius</th>
<th>Shell Inside Radius</th>
<th>Shell Outside Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Dimensions</td>
<td>12.473 mm</td>
<td>12.548 mm</td>
<td>25.096 mm</td>
</tr>
<tr>
<td>Final Dimensions</td>
<td>12.491 mm</td>
<td>12.491 mm</td>
<td>24.948 mm</td>
</tr>
</tbody>
</table>

2.3 – Results and Conclusions

Residual compressive radial stresses were present in the core and shell at the interface after the assembly was simulated, signifying that the thermal shrink fit method is capable of producing a successful bimetallic axle preform. Graphs of the full residual radial and hoop stress distributions are presented in Appendix A1 and a graphical depiction of the radial stress distribution is presented in Figure 2.1.
Although this process is capable of producing a successful preform, it does have significant limitations. As with any thermal shrink fit process, manufacturing tolerances on both the core and shell must be carefully controlled to maintain predictable residual stresses. Care must also be taken that ice does not condense on the chilled core’s surface before assembly as it has the potential to create an interstitial layer of moisture in the final product. This layer could potentially cause corrosion and/or lubricate the core-shell interface, increasing the chance that the core will slip inside of the shell instead of carrying torque. Thermal shrink fit is a viable method for producing a bimetallic preform, but is not recommended due to the high cost and complexity inherent to the process.
Chapter 3  
Press Fit

3.1 – Process Description

Press fits, also known as interference fits or force fits, are commonly used to attach gears to shafts and lock pins into holes. To obtain the fit, the male component’s diameter is made slightly larger than the diameter of the hole in which it will be inserted. This radial interference causes both components to elastically deform as the insert in pressed into the collar, forming regions of residual elastic strain. The residual elastic strain produces normal stresses at the component interface, in turn causing frictional stresses which impede sliding between the mating surfaces.

Increasing the radial interference increases the magnitude of resultant normal stresses and increasing the contact length increases the frictional surface area. Both of these factors directly influence the amount of force or torque required to initiate sliding between the contact surfaces, allowing press fits to be adjusted to meet each application’s needs. However, increasing the radial interference or contact length also increases the amount of axial stress in the male component during the pressing operation. If the axial stress reaches the material’s compressive yield stress, no further assembly is possible; additional force will cause yielding failure in the male component.

3.2 – Simulation Model

In this model, the steel shell was given a 10° lead-in chamfer with a 20 mm blended fillet on the inside diameter to promote smoother insertion of the aluminum core. The aluminum core’s outer radius was also given a fillet and adjusted to 12.505 mm to produce 0.005 mm of radial interference. The initial geometry is shown in Figure 3.1.
The simulation was based on a rigid die moving at constant velocity to press the core into the shell where the latter was held in place by a fixed boundary condition at the opposite end. A shear friction coefficient of 0.4 was specified between the aluminum core and steel shell in the simulation to represent dry surface conditions. The simulation was run as a 2D axisymmetric model in elastic-plastic mode. Successful press fits do not typically involve plastic strain, but allowing the program to simulate plastic strain improved the reliability of the results and ensured that any region in the model that experienced plastic strain could be detected.

3.3 – Results and Conclusions

After the core was pressed 165 mm into the 320 mm long shell, the simulation no longer converged. Upon examination, it was found that the axial stress in the exposed core had exceeded the 6061 aluminum’s yield strength of 276 MPa [3] and no further insertion would be possible. An image depicting the yielding in the aluminum core is presented in Figure 3.2.
Figure 3.2 – Yielding in the Aluminum Core before Full Insertion

If the press fit method is used to produce a bimetallic axle preform, the outer diameter of the core and inner diameter of the shell will need to be precisely specified. This simulated model assumed 0.005 mm of radial interference between the parts, which was sufficient to prevent full insertion. A successful process would require this interference to be reduced, leaving very little room for production tolerances. Additionally, care would need to be taken to prevent the exposed core from buckling under insertion loads. The axisymmetric model used in this study did not account for buckling, but it should be noted that the large forces involved during insertion have the potential to incite buckling failure if the core is not supported.
Lubricating the interface between the aluminum core and steel shell would reduce friction and might enable insertion to be completed without yielding. However, lubrication would also reduce the residual frictional force between the components, increasing the likelihood that the core would slip inside of the shell rather than transferring torque.

After considering all relevant factors, it was decided that this assembly method is not practical for producing bimetallic aluminum-steel axles of this size. This process might still be applicable for manufacturing shorter axles, as they would require significantly less axial force to complete the press fit.
Chapter 4
Radial Forging

4.1 – Process Description

Radial forging is a process in which a workpiece is suspended by grippers at one or both ends and forged inside of a four-die forging machine. The four dies, also referred to as “hammers”, are arranged at 90 degrees to each other in a radial pattern around the workpiece perimeter and are mechanically linked to ensure simultaneous that they contact with the workpiece. In between contact by the hammers, the grippers simultaneously rotate and advance the workpiece, giving the finished piece a near-cylindrical shape. An example of a radial forging machine is shown in Figure 4.1.

Figure 4.1 – An American GFM Radial Forging Machine [1]
Current monolithic heavy duty axle preforms are formed through a radial forging process. This study's goal was to determine if a bimetallic axle can be produced by inserting a preformed aluminum core into a steel shell and then forging the assembly together to achieve sufficient contact at the interface surfaces.

### 4.2 – Simulation Model

Initial simulations performed by this study began by exploring warm-cold forging, with the steel shell at an elevated temperature and the aluminum core at room temperature. Aluminum has a much lower flow stress than steel, so the steel was heated to a warm forming temperature in order to reduce its flow stress with the intent to allow both materials to deform at a more even rate. However, it was discovered that heating the steel to 400 F did not significantly reduce the flow mismatch. Heating the steel while keeping the aluminum at room temperature also represents a more complicated and expensive production process. As a result, heating was dropped from the simulation study in favor of forging the entire assembly at room temperature.

All final simulations were run as 2D axisymmetric elastic-plastic models. Radial forging is in actuality not a true axisymmetric deformation process but the radial hammer arrangement can be reasonably approximated as a quasi-axisymmetric state. Simulating the process geometry as 2D axisymmetric instead of fully 3D significantly reduced processing time while producing sufficiently accurate results to indicate the presence or absence of interfacial contact in the preform assembly. An attempt was made to include 0.075 mm of radial clearance between the core and shell in the simulation model but this clearance was removed when the simulations did not converge. Instead, the core and shell were put into perfect contact with a friction coefficient of 0.4. In the final simulations, the radius of the core-shell assembly was reduced by 3 mm resulting in 22.6% reduction of cross sectional area. While this is a relatively low reduction, the intent was to ascertain if it was possible to generate contact between the core and shell rather than significantly modify the geometry.

Three models were used in the final simulations. In the first, a baseline was set using a simple core and shell geometry. The workpiece was held by one gripper, which is common
practice for workpieces of this size. Based on a hammer design provided by American GFM, the leading edge of the simulated hammer was set to 8°. In an actual radial forging process, the part only advances about 0.1 mm per hammer stroke in order to produce a smooth finished part. However, the models used in this study assumed 4 mm of travel per stroke in order to significantly reduce simulation time and account for the workpiece rotation between each blow. In an attempt to prevent excessive sliding between the core and shell in the simulation model, the aluminum core was recessed into the shell as shown in Figure 4.2. The first hammer stroke partially closed the shell, constricting the aluminum’s flow.

![Figure 4.2 - Recessed Initial Geometry for Radial Forging. Pre-deformed geometry is shown left. The partially closed geometry after the first hammer stroke is shown right.](image)

In the second model, a 5 mm thick steel cap was added to the leading end of the core-shell assembly to prevent flow mismatch. This cap, shown in Figure 4.3, represents additional manufacturing complexity, but effectively eliminates flow mismatch. The 5 mm end cap remained in the third model while the hammer’s leading edge was changed to 12°. Simulating these additional models provided a basis for comparison with respect to the effects of different workpiece and tool geometries.
4.3 – Results and Conclusions

All three simulated models showed compressive residual radial stress at the core-shell interface. This indicated the presence of normal stresses between the core and shell, meaning that solid contact had been achieved and the bimetallic preform assembly was successful in all cases. Residual radial and hoop stress distributions for all three simulations are presented in Appendix A2. Figure 4.4 shows the radial stress pattern present in the case with an 8° tool angle and workpiece end cap.
In comparing the first and second simulations, it can be seen from the stress distributions that the workpiece geometry did not significantly affect the residual radial stress pattern. In both simulations, the center of the core retained 190-200 MPa of compressive stress and the normal stresses at the core-shell interface were 130-150 MPa. Hoop stress was affected more strongly, especially near the interface. The open-ended workpiece’s core hoop stress approached zero, while the shell’s hoop stress was approximately 350 MPa in compression. With an end cap, the disparity between core and shell hoop stress at the interface was greatly reduced. Core stress in this region was approximately 60 MPa and shell stress was approximately 130 MPa. This reduction in hoop stress disparity indicates that the end cap geometry limited flow mismatch between the steel and aluminum more effectively than the
partially closed shell in the first simulation, although interfacial contact strength is very similar in both cases.

Changing the hammer’s leading edge from 8° to 12° affected the residual stress pattern much more significantly, as can be seen by comparing the second and third simulations. When the capped workpiece was forged by the 12° tool, residual stresses were approximately half of those remaining from the 8° tool pass, signifying that contact is not as solid after a 12° tool pass. This conclusion is further indicated by the residual hoop stress distribution. When an 8° tool was used, residual hoop stress remained compressive throughout the entire core. In the simulation which used a 12° tool, the hoop stress became tensile near the core-shell interface, signifying that a portion of the core’s compressive radial stresses were contained within the core and not transferred across the interface as normal stresses.

The three models which were simulated by this study demonstrate that radial forging is capable of producing successful bimetallic axle preforms. On this basis, the process is recommended for further study regarding this application.
Chapter 5
Forward Extrusion

5.1 – Process Description

Forward extrusion processes are economical and currently used to form a wide variety of products from various materials. Besides creating specialized shapes, extrusion processes can also be used to reduce cross sections. The goal of this part of the study was to determine if a forward extrusion process can be used to produce a bimetallic axle preform through cross sectional reduction. The first step of this process would be to insert a preformed aluminum core into a preformed steel shell. The assembly would then be forced through an angled die to eliminate the gap between the materials and create a solid interface.

5.2 – Simulation Model

Due to the inherent symmetry, the extrusion process was simulated as a 2D axisymmetric elastic-plastic model with a cylindrical aluminum core inside of a steel shell. The steel shell was given a 2.5 mm cap on the leading end to restrict flow mismatch between the aluminum and steel. Figure 5.1 shows the core-shell assembly’s initial leading-end geometry and the outline of the reduction die. In the simulation, the core and shell assembly was pushed through the rigid reduction die by a rigid ram/dummy block. The primary die continued to force the extrusion process until the extruded form’s stress distribution no longer varied significantly with axial position. Once this steady state had been achieved, the residual radial and hoop stress distributions were analyzed to determine if solid frictional contact had been created.
Figure 5.1 – Geometry before the Extrusion Pass

The model was simulated twice, once with an 8° die angle and once with a 10° die angle, to better understand the effect of die angle on the residual stress distribution. Shallow die angles were used because it was theorized that a high angle would potentially increase the radial separation in the preform assembly before it entered the throat of the angled die. In both cases the reduced diameter was chosen to represent approximately 15% reduction in cross sectional area. Here too a small reduction in area was chosen as the intent was not to significantly change the geometry but rather to establish if sufficient contact/stress conditions could be achieved.

5.3 – Results and Conclusions

Both simulations show residual compressive radial stresses in both the shell and core at the interface surface, indicating that solid contact had been achieved. Die angle significantly affected the magnitude of this stress, which was approximately 60 MPa for the 8° die and 90
MPa for the 10° die. This suggests that die angle effects should be explored in more detail by future studies. For both dies, the residual hoop stress approached the yield strength of the 4140 steel, about 600 MPa [3], in the outermost regions of the shell. Full stress distributions are presented in Appendix A3. A visualization of the residual strain is presented in Figure 5.2.

![Figure 5.2 – Residual Strain after the Extrusion Pass](image)

Extrusion processes are widely used today to produce monolithic shapes and could be adapted with relatively few changes to produce bimetallic axle preforms. Considering all factors, the extrusion process appears to be an attractive option for producing reliable preforms and is recommended for further investigation.
Chapter 6
Interlocking Extrusion

6.1 – Process Description

All of the processing techniques presented so far rely on friction to enable torque to be transferred smoothly across the core-shell interface. The strength of this type of interface is dependent on all of the factors which can affect friction such as residual normal stresses, surface finish, and surface cleanliness. Small amounts of oil or moisture could adversely affect the finished product, as could gradual stress relaxation in the aluminum. The interlocking extrusion method is an alternative which addresses these concerns by relying on mechanical contact to transfer torque rather than friction. Strength in this kind of interface depends upon component geometry and material yield strength instead of friction.

One common form of interlocking geometry, the shaft key, is a feature used to transmit torque to/from a shaft. A similar feature could be included in a core-shell assembly to transmit torque along the entire length of a bimetallic axle. In such a design, the preformed aluminum core would include an integrated key along its entire length. This key would fit into a matching recess inside the steel shell. Figure 6.1 shows a cross section of this geometry. Both features could be produced by forward extrusion prior to assembly. Alternatively, the outer core and keyway slot might also be produced via a radial forging process using an appropriate mandrel.
Clearance must exist between any key and keyway for assembly to be possible, and this clearance translates into a proportional amount of backlash in the finished product. If not controlled, this backlash can result in harmful vibrations or damage while the assembly is in service. On normal shafts, tolerances are closely maintained to minimize or eliminate this backlash. However, holding such tight tolerances over the entire length of heavy duty truck axles would not be economical. Instead, this study sought to determine if the same extrusion process presented in Chapter 5 could close the clearance gap between the key and keyway to eliminate backlash between the shell and core.

6.2 – Simulation Model

The interlocking extrusion’s complex geometry cannot be approximated as axisymmetric. Consequently the simulation was performed using a 3 dimensional model. To reduce flow mismatch between the aluminum and steel, a 5 mm thick cap was placed on the end of the steel shell. The rigid reduction die reduced the core-shell assembly’s radius by 3 mm during the extrusion pass, translating to a reduction in cross-sectional area of 22.6%. The assembly was pushed through the reduction die using a rigid punch. Figure 6.2 depicts the initial model geometry for this simulation.
To reduce the necessary simulation time, the assembly was modeled using quarter symmetry and the initial length of the preform was reduced to 180 mm. The mesh was composed of tetrahedral elements, which do not conform to cylindrical geometry well, due to restrictions in the version of DEFORM that was used. Figure 6.3 clearly shows the tetrahedral mesh as well as the initial core geometry with integrated key.

Hexahedral elements would be better suited for acquiring accurate simulation results, but tetrahedral elements were considered sufficient for the purpose of determining whether the extrusion process had closed the clearance gap. Elastic-plastic simulations did not reliably
converge for this process, possibly due to the irregular tetrahedral surface at the core-shell interface. As a result, all presented results were taken from fully plastic simulations.

6.3 – Results and Conclusions

Residual stress distributions present in the finished simulation are presented in Appendix A4, and a visualization of residual strain is presented in Figure 6.4. Residual compressive normal stresses were present on all core-shell interface surfaces after cross sectional reduction, signifying that the clearance gaps had closed and a successful preform had been produced.

![Figure 6.4 – Residual Strain in the Extruded Interlocking Core-Shell Assembly](image)

The key-keyway interlocking geometry was chosen for simulation because of its geometric simplicity, but other geometries might be preferable for production. Hexagonal
geometries are also capable of transmitting torque effectively and hexagonal stock is already widely available to make the aluminum core. The shell could be produced as custom extruded tubing with a cylindrical outside diameter and hexagonal inside diameter. Assembling a tube and core with hexagonal geometry would be no more difficult than assembling components with cylindrical geometry, and the results obtained by this study suggest that the forming process would be successful.

The interlocking extrusion method is more complicated than the cylindrical extrusion method, but the finished workpieces are less sensitive to process conditions that could affect frictional contact at the interface. This process is recommended for further consideration for manufacturing bimetallic axle preforms.
The need to reduce vehicle weight has become increasingly crucial as regulations and customer demands continue to drive improvements in vehicle performance and fuel economy. Vehicle weight reduction begins with component weight reduction, and the monolithic steel construction of current axles makes them of particular interest as candidate parts. One possibility for reducing the weight of these components is to replace a portion of the steel with a lighter material such as aluminum. This modification allows for significant weight savings without compromising torsional strength or durability. Four different methods for achieving a bimetallic steel-aluminum preform were evaluated in this study.

1. The thermal shrink fit method was found to be capable of producing bimetallic axle preforms but is dependent on carefully controlled geometric tolerances which represent a significant increase in cost over current production methods. As such, this process is not recommended for further study.

2. The press fit technique is similar to thermal shrink fit and even more reliant on carefully controlled geometric tolerances. It also is not recommended for further study.

3. Radial forging is currently used to form monolithic heavy duty axle preforms and could potentially produce bimetallic preforms as well. This study’s simulation results show solid contact between the core and shell of a preform produced by radial forging, suggesting that the method is capable of producing a successful preform. Radial forging would also likely be cost effective and is recommended for further study.

4. Forward extrusion processes produce similar effects within workpieces, and simulations performed by this study showed promising results. Forward extrusion could be easily adapted to produce bimetallic preforms from existing processes, and thus would also be cost effective.
In consideration of the promising simulation results and expected low cost, this process is recommended for further study.

The four processes discussed above assume axisymmetric axle geometry which relies on residual normal stresses and friction to transfer torque between the core and shell. Another option is to produce axles with only partially symmetric cross sections which transfer torque through mechanical contact, such as keys or hexagons. This study simulated a forming process in which a bimetallic axle preform with an extruded key was pushed through an extrusion die and found that solid contact between the core and shell could be produced. Selecting a specific combination of geometry and forming processes for this method is not trivial and would likely be more expensive than axisymmetric radial forging or extrusion processes. However, bimetallic axles produced with interlocking geometry have the potential to be stronger than those with axisymmetric geometry as the limiting torque is dependent on the strength of the aluminum alloy.

The purpose of this study was to identify which forming processes show promise for the mass production of bimetallic heavy duty axle preforms. Of those considered, radial forging, forward extrusion, and interlocking processes appeared to be capable and cost allowable. Further study is recommended to optimize each of these approaches through finite element simulations and determine which would be most conducive to manufacturing durable, cost-effective preforms. Once a specific process is identified as being the most promising, several preforms should be produced by that process and thoroughly tested to ensure that they meet all necessary performance qualifications.
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Appendix

**Note:** All figures display residual stress distributions present in both the aluminum core and steel shell after simulation. The region of stress discontinuity, visible as a vertical line central to each curve, represents the location of the interface between the two materials.

**A1 – Thermal Shrink Fit Residual Stress Distributions**

![Residual Hoop Stress](image1)

**Figure A1.1 – Residual Hoop Stress after Thermal Shrink Fit**

![Residual Radial Stress](image2)

**Figure A1.2 – Residual Radial Stress after Thermal Shrink Fit**
**A2 – Radial Forging Residual Stress Distributions**

**Figure A2.1** – Residual Hoop Stress with 8° Hammer Angle, 4mm per Stroke, and no End Cap

**Figure A2.2** – Residual Radial Stress with 8° Hammer Angle, 4mm per Stroke, and no End Cap
**Figure A2.3** – Residual Hoop Stress with 8° Hammer Angle, 4mm per Stroke, and End Cap

**Figure A2.4** – Residual Radial Stress with 8° Hammer Angle, 4mm per Stroke, and End Cap
Figure A2.5 – Residual Hoop Stress with 12° Hammer Angle, 4mm per Stroke, and End Cap

Figure A2.6 – Residual Radial Stress with 12° Hammer Angle, 4mm per Stroke, and End Cap
A3 – Extrusion Residual Stress Distributions

**Figure A3.1** – Residual Hoop Stress after Extrusion through an 8° Reduction Die

**Figure A3.2** – Residual Radial Stress after Extrusion through an 8° Reduction Die
Figure A3.3 – Residual Hoop Stress after Extrusion through a 10° Reduction Die

Figure A3.4 – Residual Radial Stress after Extrusion through a 10° Reduction Die
A4 – Interlocking Extrusion Residual Stress Distributions

Figure A4.1 – Residual Hoop Stress in the Region without a Key

Figure A4.2 – Residual Radial Stress in the Region without a Key
Figure A4.3 – Residual Stress through the Key-Keyway Top, Normal to the Surface

Figure A4.4 – Residual Stress through the Key-Keyway Side, Normal to the Surface
References


