A comparative study of the residual deformation of an automotive gear-case assembly due to deep-penetration high-energy welding

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Abstract

A three-dimensional elastic–plastic finite element model was used to investigate the relative effects of different joint forms on the welding distortion and residual stresses in an automotive differential assembly due to deep-penetration high-energy welding. Numerical studies were carried out to determine optimal selections of heat generation rate and the number of weld segments to ensure both computational efficiency and accuracy of the calculation. To model the constraints and boundary conditions realistically, contact elements were used at the mating surfaces of different structural components and the shrink fit between the gear and differential case was modeled using couple sets. Two situations representing welded gear-case assemblies where the weld joints were oriented at 0$^\circ$ and 30$^\circ$ with respect to the radial direction were analyzed. Predicted welding distortions and residual stresses are compared and discussed in detail. The results indicate that the residual tensile stresses in the 0$^\circ$ radial joint are larger than those in the 30$^\circ$ angled joint and that residual distortion is sensitive to joint form.

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1. Introduction

High-energy welding processes, such as laser or electron beam welding, are being applied in an increasing array of industrial applications because of the narrow heat-affected zone, low residual distortion, high productivity, flexibility and lower operating costs compared to traditional joining processes [1]. In most cases, a welded construction results in a more compact design and a reduction in weight and cost of the constituent components. Due to these advantages, welded joints may be used to replace some of the conventional bolted joints between automotive transmission components, such as a gear and a differential case.

The welding process results in undesirable residual stresses and distortion. This can be particularly critical for precision components such as automotive transmission gearing. Because it is impossible to obtain the experimental data of every situation, computer simulations of welding processes are needed in order to predict the impact of different design options on residual stress and deformation. Finite element simulation has become a proven and reliable technique for prediction of welding deformations and residual stresses. However, finite element simulations are currently only used in applications where safety aspects are very important or when a large economic gain can be achieved [2]. The time and cost associated with reliable analysis of complex industrial problems appear to be the main reason contributing to this practice.

Investigators have attempted to develop strategies focusing on different dominant factors that influence the efficiency of modeling actual welded structures [3–7]. In this study, by considering the influences of heat generation rate, intersegmental cooling time and the number of weld segments a strategy for the moving heat source with high power density, as the result of a compromise between accuracy of the model and the required computational time, was investigated by numerical analysis. A simplified FE (finite element) model was employed to study the impact of joint form on the residual stresses and distortion of a welded automotive differential consisting of a gear welded to a differential case.

2. Finite element model

The aim of this study was to evaluate the impact of different joint forms for the high-energy welding of a gear to a differential
case on residual stress and gear distortion. Two cases with different joint forms were analyzed and compared for their relative effects:

- Case I: welding of gear-case assembly with 0° radial joint.
- Case II: welding of gear-case assembly with 30° angled joint.

2.1. Mesh generation

Fig. 1 shows the two types of joint form under study. As illustrated, the two joint forms considered differ in the inclination angle of the incident laser beam with respect to the radial direction, which is 0° for the radial joint and 30° for the angled joint.

The geometry of the gear-case assembly with the 0° radial joint is shown in Fig. 2(a). Shown in Fig. 2(b) is the finite element mesh for the assembly with a 0° joint (case I). This model consisted of 11,639 solid elements and 28,867 nodes. The geometry of this assembly was modeled using two types of solid elements, high order 20-node brick elements for the weld area and 10-node tetrahedral elements for the region far away from the weld. A dense mesh was used up to a distance of 8 mm on both sides of the weld centerline, as shown in Fig. 2(c) and the element size increased progressively with distance from the weld centerline. The minimum element size in the model was 0.5 mm × 1 mm × 1.75 mm.

To ensure a balanced comparison between the analysis results for each case, the same meshing scheme used for case I was also used for case II.

Fig. 1. Cross-section of the two joint forms considered in this study. (a) 0° (radial) joint; (b) 30° angled joint.

Fig. 2. Schematic drawing of the mesh. (a) Solid model; (b) finite element mesh; (c) mesh in the vicinity of the weld.
2.2. Material properties

The thermal and mechanical properties employed in this study are shown in Fig. 3. The material used for the differential case was SAE15V24, while the material used for gear was SAE8822. The material properties of the weld were assumed to be the average of those of the case and the gear. The plastic behavior of the materials was described by the von Mises yield function and bilinear isotropic hardening was assumed. For simplicity, it was assumed that phase transformation occurred over a temperature range and that the associated latent heat was averagely distributed over this temperature range.

2.3. Boundary conditions

In thermal analysis, the thermal load was applied at a nodal heat generation rate corresponding to a volume of internal heat generation power progressing along the weld line during analysis. Surface effective elements were used to simulate convection to the environment from all exterior faces of the assembly. Radiation heat loss was neglected.

In the FE model for case I, the nodes on face A, shown in Fig. 4(a), were constrained in all three directions for structural stability of the model. To simulate the influence of an interference fit between the gear and the case as shown in Fig. 4(b), contact elements were used at the mating surfaces and a contact pair was created. For simplicity, the shrink fit between faces B and C, shown in Fig. 4(a), was modeled as a couple set. All degrees of freedom of the nodes on faces B and C were coupled, respectively. In addition, four initial tack welds at angular positions of 0°, 90°, 180° and 270° from the weld start position were applied. Each tack weld had a length of 50 mm and penetration of 3.5 mm. For simplicity, the influence of any stresses induced by tack welding was ignored in the analysis.

The boundary conditions used for case II were identical to those used for case I, except that contact elements were not used for case II where there was a gap between the gear and case, as shown in Fig. 1(b).

2.4. Analysis procedure

Commercial FE software ANSYS was used to solve the model. The problem was treated as a sequentially coupled analysis. First, a nonlinear transient thermal analysis was performed to predict the temperature history of the model. Subsequently, temperature results of the thermal analysis were applied as body loads in a nonlinear transient thermal–mechanical analysis to calculate deformation. The same mesh used in the thermal analysis was used for the thermal–mechanical analysis with differing element types. During welding, the temperature, and consequently the temperature dependent material properties, changed very rapidly. Thus, a full Newton-Rhapson iterative solution technique, which updated material properties and the stiffness matrix at every equilibrium iteration, was used. Element birth/death technique was used to deal with the metal melting that occurred during welding. Elements with a temperature higher than the melting point had no mechanical effect on the surrounding elements, so ANSYS program deactivated these melted elements by multiplying their stiffness by a severe reduction factor, which defaulted to 1.0E−6.

3. Optimization of the moving heat source model for the high-energy keyhole welding process

Proper modelling of the heat source is crucial as it controls the thermal load, and consequently the weld-bead profile [8,9]. The so called prolonged heat source model was used in this study [10]. The whole weld bead was divided into several segments
of equal length. A volumetric heat source was employed in the thermal analysis. The continuous welding process was approximated by welding each segment in turn. Shown in Fig. 5 is the weld segment to which the thermal load was applied, over which the heat generation rate was constant. In Fig. 5, \( L \) is the length of a weld segment.

Before useful results could be obtained through the prolonged heat source model the effects of following variables needed to be understood:

1. Heat generation rate.
2. Number of weld segments.

### 3.1. Effect of heat generation rate on weld geometry

The mechanism of deep-penetration high-energy welding is quite different from conventional welding techniques. During deep-penetration high-energy welding a keyhole forms in the work-piece and the beam is reflected repeatedly within it. Fresnel absorption occurs at the keyhole walls, thus increasing the coupling of beam energy into the work-piece. As the keyhole develops, the power of the source can be absorbed at greater depths, leading to the high aspect ratio of the weld bead. Furthermore, it is known that there exists a very thin layer of several mean free paths, called the kinetic Knudsen layer, just outside the liquid/vapor interface. Across this layer, continuum hypothesis fails and steep changes in temperature, pressure and density occur. Therefore, the interface was treated as a mathematical discontinuity, for which the jump conditions were derived by Knight [11].

In this study, the appropriate heat generation rate was achieved by manual adjustment of the parameters and comparison with an experimentally attained fusion boundary profile. The simulation parameters are given in Table 1. The actual weld cross section was compared with the calculated weld cross section in Fig. 6. According to this result, the heat generation rate was specified as 1500 W/mm³ in this study. The duration of the thermal load on each segment, \( \Delta t_{\text{heat}} \), was formulated as follows:

\[
Q = h_{\text{gen}} \Delta t_{\text{heat}} V
\]

\( Q \) is the total heat input of each segment, \( V \) the volume of each segment and \( h_{\text{gen}} \) is the heat generation rate. The total heat input of each segment \( Q \) is determined by

\[
Q = \eta P \left( \frac{L}{v} \right)
\]

where \( L \) is the length of a segment and \( v \) the traveling speed of laser beam and \( P \) is the total output power of the heat source. A coupling efficiency \( \eta \) was introduced as not all of the power is absorbed by the work-piece.

### 3.2. Effect of the number of weld segments on the analysis results

A larger number of segments lead to more accurate analysis results. However, excessive number of weld segments also results in unacceptable computational cost. Thus, investigations were carried out to determine at what number of segments would optimize the CPU time with acceptable simulation accuracy. Because this kind of investigation may be very time consuming, a simplified model was developed which was similar in overall geometry to the gear-case assembly but was axisymmetrical and did not include the gear teeth and ribs, which would have dramatically increased the size of the model. The simplified model is shown in Fig. 7. The new model with reduced size had 9920 elements.

The impact of the number of weld segments on the analysis results were studied using the simplified model. The variation of the residual distortion with the number of weld segments is

<table>
<thead>
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<th>Variables</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>Heat generation rate</td>
<td>W/mm³</td>
<td>1500</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Focal point diameter</td>
<td>mm</td>
<td>0.32</td>
</tr>
<tr>
<td>Weld time</td>
<td>s</td>
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shown in Fig. 8. It can be seen that with an increasing number of weld segments, the axial displacement of the low points decreased continuously, while the radial displacement of low points and high points and the axial displacement of high points increased. The resulting displacement curves for 120 segments are similar to those for 60 segments, which indicates the onset of convergence between 60 and 120 weld segments. Based on these results, it was concluded that analysis with 60 weld segments would optimize the CPU time and the simulation results. Subsequent analyses were therefore run with 60 weld segments.

The whole weld bead was divided into 60 even segments. The heat generation rate was 1500 W/mm³ as discussed in Section 3.1 and intersegmental cooling time was calculated by the dividing the segment length by the welding speed. In the thermal analysis the total circumferential welding time of 40 s was divided into 540 solution steps. The program determined the number of sub-steps automatically. Another 40 load steps of different time duration were used for the cooling of the workpiece. Load step time in the thermal–mechanical analysis was identical to that in the thermal analysis. Total run time was about 185 h for the thermal–mechanical analysis using an HP XW4100 workstation with 3.2 GHz CPU and 1 GB RAM.

4. Results and discussion

Based on the methodology introduced in Sections 2 and 3, the effects of joint form on the residual stresses and distortions of the gear-case assembly were investigated. All parameters and boundary conditions used in the analyses for case I were identical to those used in the case II analysis, except that contact elements were not used for case II.

Because the final displacements of the high points and low points indicated in Fig. 1 are the main focus of this study,
Fig. 9 shows the effects of joint form on the residual distortion. As shown in Fig. 9(a), the radial displacement of the 30° angled joint model is slightly less than that of the 0° radial joint model, which mainly results from the fact that the transverse shrinkage direction of the weld in the 0° radial joint model is perpendicular to the radial direction.

Fig. 9(b) shows the axial displacements of the low points. It can be seen that the axial displacements of the low points in the 30° angled joint model fluctuated more significantly than those of the low points in the 0° radial joint model. From 60° to about 330°, the axial displacement of the low points of the 30° angled joint model was greater than that of the 0° radial joint model. The main reason for this phenomenon is that the transverse shrinkage direction of the weld in the 0° radial joint model was identical to the axial direction of the coordinate system, while the transverse shrinkage direction of the weld in the 30° angled joint model was not. In the vicinity of the welding start position (0° hoop coordinate), the low points’ axial displacement of the 30° angled joint model was significantly less than that of the 0° radial joint model. This is due to the fact that contact elements, which would resist the transverse shrinkage of weld during the cooling phase, were employed at the mating faces for the 0° radial joint model but not for the 30° angled joint model.

The radial displacements of the high points in the 0° radial joint model are compared with those of the high points in the
30° angled joint model in Fig. 9(c). The plot reveals that radial
displacements of the 30° angled joint model were about 30% less
than those of the 0° radial joint model. Fig. 9(d) shows the axial
displacement of the high points. It is illustrated that the axial
displacement of the high points of the 0° radial joint model was
about 20% greater than that of the 30° angled joint model in all
angular orientations.

Fig. 10 shows the final displacement difference between the
high points and low points in the radial and axial directions. It
should be noted that both radial and axial displacement dif-
fERENCE increased after welding no matter which joint type was
adopted. In addition, Fig. 10 illustrates that the radial and axial
displacement differences of the gear-case assembly with the 30°
angled joint was more fluctuant than those of the 0° radial joint
assembly.

The lack of the axial symmetry of the displacements in
Figs. 8–10 is attributed to the fact that a moving heat was applied
to the nodes or elements along the weld line. The heat application
to the part at any given time step was not symmetric.

Results of residual stress fields at the cross section through
the 90° hoop coordinate in the 0° radial joint model are presented
in Fig. 11. At the later stage of cooling the shrinkage of the inner
portion of the weld was constrained by the surrounding material.
Thus, the shrinkage of the weld created tensile residual stresses
in the inner portions and compressive residual stresses in the sur-
rounding material. This can be explained based on the force bal-

![Fig. 11. Stress fields in 0° radial joint at the cross section through the 90° hoop coordinate. (a) Radial stress field; (b) hoop stress field; (c) axial stress field.](image1)

![Fig. 12. Stress fields in 30° angled joint at the cross section through the 90° hoop coordinate. (a) Radial stress field; (b) hoop stress field; (c) axial stress field.](image2)
ance between the stresses near to and away from the weld. It can be seen from Fig. 11 that the peak tensile stresses for each stress component always occurred at the central region of the fusion zone. In addition, the peak radial tensile stress was the largest in all directions in the 0° radial joint model. The radial stresses decreased with increasing distance from weld center, passing through zero at about 5 mm from the weld center in axial direction and leading to balancing compressive stresses in far field.

Fig. 12 shows the distribution of residual stresses at the cross section through the 90° hoop coordinate in the 30° angled joint model. It can be seen from these figures that the peak tensile stresses were generated at the central region of the weld, a situation similar to that of the 0° radial joint model. These figures also reveal that, in the 30° angled joint model, the peak axial tensile stress is larger than peak tensile radial stresses and peak tensile hoop stresses. The largest axial tensile stress in the 30° angled joint model was about 270 MPa, which was smaller than that in the 0° radial joint model. As shown in Fig. 12, there was no tensile stress in the region near the top surface of the weld in the 30° angled joint model, which was substantially different from the 0° radial joint results illustrated in Fig. 11.

5. Conclusions

The high-energy deep-penetration welding process for an automotive transmission gear-case assembly was modeled using finite element analysis. The relative effects of joint form on the residual stresses and resulting distortions were investigated using optimized FE models. Based on these investigations, the following conclusions can be offered:

(1) The change of the joint type from 0° radial joint to 30° angled joint led to about 19% increase in low points’ axial displacement, about 10% decrease in low points’ radial displacement, about 24% decrease in high points’ radial displacement and about 9% decrease in the axial displacement of high points.

(2) In the 0° radial joint model, the radial tensile stresses were larger than tensile stresses in other directions, and the largest tensile stress of approximately 370 MPa appear in the center of the weld. In the 30° angled joint model, the axial tensile stresses were larger than tensile stresses in other directions, and the largest axial tensile stress was about 270 MPa.

The results indicate that residual distortion in the gear-case assembly is highly sensitive to joint form and that a 0° radial joint generates higher tensile stress than a 30° angled joint. The results of this study may help to select the joint form in fabricated automotive transmission applications and the methodology reported here would be beneficial to researchers attempting to tackle similar problems.

Acknowledgments

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