ABSTRACT

This paper review the results from two recently completed comparative studies, one for a suspension component (steering knuckle) and another for an engine component (connecting rod). The steering knuckles evaluated included forged steel, cast aluminum, and cast iron knuckles. The connecting rods evaluated consisted of forged steel and powder metal. Fatigue behaviors of these components made of competing manufacturing technologies are compared and results of fatigue life predictions and optimization studies for the components investigated are presented. Effects of manufacturing alternatives and costs, material behavior, and processing conditions such as surface finish and residual stresses are discussed.

INTRODUCTION

There has been a strong trend towards the adoption of optimum materials and components in automotive industry. Automotive designers have a wide range of materials and processes to select from. Steel forgings are in competition with aluminum forgings and castings, cast iron, and sintered powder forgings. It is not unusual to find a range of different materials and manufacturing technologies employed within modern chassis and engine components.

The objectives of this study were to evaluate and compare fatigue performance and assess fatigue life for a chassis component (steering knuckle) and an engine component (connecting rod). For the steering knuckle, the competing manufacturing processes are steel forging and casting (aluminum and iron). For the connecting rod, the typical competing manufacturing processes are steel forging and powder metal. Both components are fatigue critical components.

In this paper, first component fatigue test results for steering knuckles and connecting rods are presented and fatigue performance from competing manufacturing methods are compared. Life predictions are then made for both components and the results are compared with component test results. For the steering knuckles, both the S-
N and strain-life approaches to fatigue life prediction are used. For the connecting rods, only the S-N approach is used due to the mainly elastic stresses, as a connecting rod has to survive very long life. Finally, results of optimization studies for both the forged steel steering knuckle and the forged steel connecting rod are presented. To accomplish this for the connecting rod, dynamic load analysis was required due to the significant inertia force present.

The results presented in this paper are based on two recently completed studies. The study of the steering knuckle was funded by the Forging Industry Educational and Research Foundation (FIERF) as well as the American Iron and Steel Institute (AISI). The connecting rod study was funded by AISI. Both studies included extensive literature reviews, experimental studies including both material tests using standard test specimens as well as component bench tests, and analytical investigations including detailed finite element stress analysis as well as fatigue and optimization studies. Details of the experimental and analytical procedures used as well as results obtained and their discussion can be found in (1-4) for the steering knuckle study, and in (5-8) for the connecting rod study.

FATIGUE PERFORMANCE COMPARISONS

Steering Knuckle

Knuckles of three vehicles with different manufacturing processes were selected. These included forged steel SAE Grade 11V37 knuckle of the rear suspension of a 4-cylinder sedan weighing 2.5 kg, cast aluminum ASTM A356-T6 knuckle of front suspension of a 6-cylinder minivan weighing 2.4 kg, and cast iron ASTM A536 Grade 65-45-12 knuckle of the front suspension of a 4-cylinder sedan weighing 4.7 kg. Only the forged steel knuckle included the spindle portion. Figure 1 shows the digitized models of the three components.

To obtain stress-life behavior of the components and to be able to compare the fatigue behavior of the knuckles, constant-amplitude load-controlled fatigue tests were performed for forged steel and cast aluminum knuckles. The suspension system of each vehicle that the component belongs to was identified and the loading and attachment conditions of the knuckle in each vehicle were investigated. These attachments were considered as the primary restraint and loading conditions of the test, respectively. The critical points of highest stress in the component were obtained from finite element stress analysis. A closed-loop servo-controlled hydraulic load frame was used to conduct the bench tests.

Displacement amplitude versus cycle data of the component during each test was monitored in order to record macro-crack nucleation (i.e. a crack on the order of several mm), growth, and fracture stages. Due to the nature of the loading and restraints on both knuckles, the locations of crack initiation could not be reached to
enable detecting crack nucleation. Therefore, a marked displacement amplitude increase during the test was considered as the crack nucleation point, and a sudden increase as the final fracture. For the forged steel knuckle the displacement amplitude was nearly constant until about the end of the test. This indicates that the time lag between macro-crack nucleation and fracture was a small fraction of the total life. On the other hand, for the cast aluminum knuckle, the crack growth portion of the life was significant. For a typical cast aluminum knuckle the crack lengths were 8 mm, 13 mm, 20 mm and 27 mm at 30%, 50%, 70% and 90% of total life, respectively.

The stress amplitude versus life curves of the two knuckles are superimposed in Figure 2. For the cast aluminum knuckle S-N lines based on failure defined as either macro-crack nucleation or fracture are shown. As can be seen, on the average, about 50% of the cast aluminum knuckle life is spent on macro-crack growth. This figure also shows that the forged steel knuckle results in about two orders of magnitude longer life than the cast aluminum knuckle, for the same stress amplitude level. This occurs at both short as well as long lives. Note that that the difference can be even larger at long lives, due to the run-out data points for the forged steel knuckle. It could also be seen from this figure that the highest load levels provided life in the range of $10^4$ to $5 \times 10^4$ cycles. Load levels corresponding to this life range are considered to be representative of overload conditions for suspension components, such as a steering knuckle in service.

**Connecting Rod**

Powder metal connecting rods with a weight of 570 g used in a mini-van 2.4 L engine, and forged steel connecting rods with a weight of 455 g used in a midsize car 2.3 L engine were chosen. The forged steel rod was made of carbon steel with 33% carbon and powder metal connecting rods contained 2% copper. While the powder metal connecting rods were shot peened for improved fatigue resistance, the forged steel connecting rods did not require shot peening, as the compressive residual stress formed on the surface from the shot blasting operation during the cleaning process was sufficient for improved fatigue resistance. Figure 3 shows pictures of the forged steel and powder metal connecting rods.

Axial fatigue tests of the forged steel and powder metal connecting rods were performed to assess and compare fatigue behaviors of the two connecting rods. Alignment of connecting rod with respect to the load-train was carefully made before the axial fatigue tests were conducted. To minimize misalignment, a ball joint pin was introduced at the bottom of the test fixture. The same fixtures were employed to test both forged steel and powder metal connecting rods, using corresponding pins for each type of connecting rod. Three tests were conducted at each load level, to assess variability and scatter. All the connecting rods were tested at a load ratio of $R = -1.25$.

The dominant fracture location of the powder metal connecting rods was near the transition region to the pin end. The forged steel rods mainly failed at or near the transition to the crank end region. Figure 4 shows the stress amplitude versus number of cycles to failure. Forged steel connecting rod fatigue strength, defined at $10^6$ cycles,
is 387 MPa, whereas for the powder metal connecting rod it is 282 MPa. Therefore, the forged steel connecting rod exhibits 37\% higher fatigue strength, as compared with the powder metal connecting rod. This increased strength results in about two orders of magnitude longer life for the forged steel connecting rod. With longer lives, the two S-N lines diverge, so that the difference in fatigue performance between the two connecting rods increases.

Directional property of the material is an important factor in its durability performance. In hot forging, the directional solidification of grains is desired for better fatigue strength. In PM connecting rods, there is no strengthening effect obtained by forging, whereas the grain flow in one direction (primary loading direction) during the forging process of steel connecting rods can provide additional fatigue strength.

**LIFE PREDICTIONS**

**Steering Knuckle**

The Basquin equation was used to obtain the fatigue life:

$$ \sigma_{nf} = \sigma_f (2N_f)^b $$

(1)

Normally a surface finish reduction factor is applied to the fatigue strength of a component. However, the fillet of the forged steel knuckle was machined and polished and, therefore, no surface finish factor was applied. For the two cast knuckles, due to the nature of the casting materials and the fact that the defects of a casting material is uniform internally and externally, no surface finish factor was implemented either.

In the strain-life approach, the local values of stress and strain at the critical location were used to find fatigue life, according to the Smith-Watson-Topper (SWT) parameter that considers the mean stress effect:

$$ \sigma_{\text{max}} e_a E = (\sigma_f')^2 (2N_f)^{2b} + \sigma_f' e_f E (2N_f)^{b+c} $$

(2)

Superimposed stress amplitude versus life curves based on stress-life approach, and SWT parameter versus life based on the strain-life approach for the three knuckles are presented in Figures 5 and 6, respectively. Component test data for the forged steel and cast aluminum knuckles are also superimposed in these figures for comparison with predictions. Figure 5 indicates that predictions based on the S-N approach are overly conservative for both the forged steel and cast aluminum knuckles. The predictions based on the SWT parameter are closer to the experimental results, as shown in Figure 6. Comparison of the forged steel and cast iron knuckle prediction curves in Figure 6 demonstrates that the forged steel knuckle offers more than an order of magnitude longer life than the cast iron knuckle, at both short as well as long lives. As compared with the cast aluminum knuckle, the predicted lives for the forged steel knuckle are longer by about three orders of magnitude.
In the forging process, hot working refines grain pattern and imparts high strength and ductility, whereas castings are weaker in this respect. In addition, lower ductility of castings limits their capacity for cyclic plastic deformation which often occurs at stress concentrations and at overloads, and therefore shortening their fatigue lives. Residual stresses at the critical locations of the component generated during the manufacturing process could be a significant source of strengthening (if compressive) or weakening (if tensile), in terms of fatigue life.

**Connecting Rod**

The stress-based approach to fatigue is typically used for life prediction of components subject to high cycle fatigue, where stresses are mainly elastic, as in the case of connecting rods. This approach emphasizes nominal stresses rather than local stresses. It uses the material stress-life curve and employs fatigue notch factors to account for stress concentrations, empirical modification factors for surface finish effects, and analytical equations such as the modified Goodman equation to account for residual and/or mean stress effects (9).

The material S-N line is given by eq (1). To account for the effect of stress concentration (i.e. at the shank transition region), the fatigue notch factor, $K_f$, is calculated based on $K_n$, the notch radius, as well as strength of the material. The modified Goodman equation is often used to account for the effects of mean and/or residual stresses:

$$\frac{S_a}{S_{Nf}} + \frac{S_m}{S_u} = 1$$

(3)

where $S_a$ is the stress amplitude (alternating stress), $S_m$ is the mean stress, $S_u$ is the ultimate tensile strength, and $S_{Nf}$ is the smooth fatigue strength with no mean stress.

To account for surface finish effect, fatigue strength, $S_f$, of a smooth component at $10^6$ cycles is multiplied by the empirical surface finish factor, $K_s$. This factor for steels is estimated based on the type of surface finish and the material strength from Figure 7, which was first produced by Juvinall [10]. For the forged surface finish of the two connecting rods and based on the ultimate tensile strength of the two materials, a $K_s$ value of 0.3 was obtained for both the forged steel and PM connecting rods.

The comparison of experimental data and predicted lives for forged steel connecting rod is shown in Figure 8. As can be seen, the S-N approach predictions are very reasonable, if the predictions are based on smooth surface finish, rather than forged surface finish. This is because the beneficial compressive residual stresses on the surface from the shot blasting process nullify the detrimental effect of forged surface finish. This was manifested by subsurface crack nucleation. It is speculated, however, that even without the compressive surface residual stress, the effect of forged surface finish, as estimated based on empirical surface finish factor $K_s$ shown in Figure 7 is overly conservative. Despite the importance of surface finish in life predictions and fatigue analysis, there is very little data in the open literature, other than the graph in
Figure 7 first published in 1967. This graph is reproduced and referred to in many mechanical design as well as fatigue design textbooks. As can be seen from this figure, the effect of forged surface finish on fatigue life is indicated to be very severe, even though such severe effect was not observed experimentally for the forged steel connecting rod, as illustrated in Figure 8. Therefore, realistic quantitative data on the effects of forged surface finish and residual stresses are needed.

The predicted fatigue lives are plotted versus experimental fatigue lives for forged steel as well as powder metal connecting rods in Figure 9. The $45^\circ$ diagonal line represents the perfect prediction line. Data points above this line indicate over prediction, and data points below this line represent conservative predictions. Factors of 2 and 3 lines are also plotted in the figure. It can be seen that nearly all the data fall within a factor of $\pm 3$ prediction lines.

OPTIMIZATION

Steering Knuckle

The objective of the optimization study was to reduce weight and manufacturing cost of the forged steel steering knuckle while maintaining or improving its fatigue strength. Manufacturing costs and fatigue strength of a steering knuckle depend on service conditions, geometry, material and manufacturing processes. Service conditions are typically dictated to the designer. Therefore, geometry, material and manufacturing parameters were attempted in this study as design variables. The modifications were approached in two stages; first without changing the component’s attachment geometry and focusing on steering knuckle’s body; and second, with limited change in attachment geometry and focusing on the spindle as well as the body. The material alternatives considered replacing the current material with materials of superior fatigue performance, and subsequently, reducing dimensions and weight. Manufacturing parameter modifications to improve fatigue performance or reduce manufacturing costs included precision forging instead of conventional forging, warm forging instead of hot forging, reducing manufacturing steps, and surface enhancement.

The forged steel steering knuckle’s material (11V37 steel) is a resulphurized (free machining) high-strength low-alloy (or microalloyed) steel. Microalloyed forging steels reduce manufacturing costs by means of a simplified thermo-mechanical treatment (i.e., a controlled cooling following hot forging) that achieves the desired properties without additional heat treatments (i.e. quenching and tempering) required by conventional carbon and alloy steels. However, limited weight saving could be achieved by replacing the potential alternative materials for the steering knuckle in this study, mainly due to the geometrical constraints. If comprehensive changes to the geometry were allowed or for other components with fewer constraints, the weight saving would be more significant.
The steering knuckle’s main manufacturing processes are hot forging and machining. Figure 10 shows the manufacturing process flow chart. A realistic optimization process necessitates a good understanding of the production cost attributes and engineering parameters that influence them in manufacturing of the component. These are shown in Table 1 for the forged steering knuckle. In manufacturing of the steering knuckle, the cost attributes of a unit steering knuckle consist of the raw material, forging process and machining process costs. The cost of each process consists of variable and fixed costs. The overhead costs include energy consumption during the processes. The inspection costs depend on the design and customer requirements. The cost of the forged steering knuckle including the raw material is 50% of the finished part cost and the remaining 50% is the machining process’s share.

The overall optimization approach was a combination of quantitative and qualitative methods (i.e. mass reduction, cost reduction, and improving fatigue performance using alternative materials and considering manufacturing aspects). The optimization work was performed in two stages. Figure 11 shows a schematic of the alternatives considered. In Stage I with no changes in attachment geometry, the geometry variables were considered to be the thicknesses at different locations of the body while considering manufacturing limitations. Additional manufacturing modifications to reduce cost were also investigated. In Stage II with limited changes in the attachment geometry, the spindle was redesigned and alternative materials and additional manufacturing operations were investigated to reduce weight and cost. For each optimization stage, a localized shape optimization procedure was used on the steering knuckle considering manufacturing limitations. The material and manufacturing processes as design variables were more used as means of design modification rather than optimization.

The current practice in the forging of steering knuckle results in some material being wasted as flash, in addition to generating less precise parts that require machining for the required tolerances at the interfaces with other suspension parts. Precision forging reduces the amount of machining and the associated cost significantly. However, precision forging requires more complex dies that need to be replaced more often, and higher forging loads that may increase the production cost of the component.

The current forging process of the steering knuckle of this study is performed hot. Warm forming is an energy efficient process that allows for a part to be manufactured to a near net shape, in fewer operations, and with less material waste than in hot forming. By nature, warm forging results in a significant refinement of the austenite grain size. Warm forging does, however, have limitations and requires specialized equipment due to the fact that the resultant forming pressures in this process are extremely high. Since the press load capacities are higher than that required for hot forging a similar size part, the tooling must be able to withstand the higher stress levels imparted during forging. This places an overall limitation on the size of forging that can be formed at lower temperatures. Therefore, while substituting warm forging was considered as one of the
options in manufacturing process modification of the steering knuckle, it is necessary to evaluate the cost impact of the option in a more detailed study.

Additional manufacturing operations such as surface rolling at the spindle fillet, carburizing, nitriding, surface hardening, and shot peening to induce compressive residual stress could also be considered to further improve fatigue strength of the component. These modifications should be investigated at the detailed design stage, considering the issues of manufacturability and cost.

The resulting optimized geometries for the two stages are shown in Figure 12. Table 2 provides a comparative list of component’s original weight and the weight reductions of each optimization stage. Overall weight and cost reductions of at least 12% and 5%, respectively, are estimated for the manufacturing process. The cost of the saved material is additional reduction, though not very considerable due to small portion of material cost within the total production cost. The optimization results show somewhat limited changes for this particular component. First, this component is relatively small, compared to steering knuckles with similar or relatively similar service conditions. Second, it has many attachment compatibility constraints. In spite of the limited optimization achieved for this particular component, the approach that was followed is applicable to other forged components. Components with fewer geometrical restrictions have much higher potential for weight reduction and cost savings.

Connecting Rod

Optimization was performed for the steel forged connecting rod with a consideration for improvement in weight and production cost. Since the weight of the connecting rod has little influence on its total production cost, the cost and the weight were dealt with separately. The optimization carried out, therefore, is not in the true mathematical sense, since while reducing mass, manufacturing feasibility and cost reduction are integral parts of the optimization.

The optimization was performed under a cyclic load comprising dynamic tensile load and static compressive load as the two extreme loads. Results consisting of the angular velocity and angular acceleration of the connecting rod, linear acceleration of the connecting rod crank end center and of the center of gravity, and forces at the ends were generated for a few engine speeds. Crank end and piston end forces as a function of crank angle for this connecting rod at the maximum engine speed of 5700 rev/min are shown in Figures 13(a) and 13(b), respectively. At any point in time the forces calculated at the ends form the external loads, while the inertia load forms the internal load acting on the connecting rod. As can be seen, the maximum dynamic tensile load corresponds to 360° crank angle. Note that under the effect of dynamic load, forces at the two ends are different at a given instant of time.

Quasi-dynamic FEA was performed to obtain the stress-time history. Quasi-dynamic FEA rather than static FEA can capture the actual connecting rod structural behavior. The stress-time history at the top (location 9) and two opposite points in the middle of the I-beam section (points 12 and 13) are shown in Figure 14. From this figure
it is clear that the maximum stress at location 9 occurs at 360° crank angle, just as it
does for the maximum load. At location 13, however, the maximum stress occurs at
348° crank angle, due to the influence of bending stresses. This highlights the
significance of the bending stresses, which will not be considered if designing/optimizing
connecting rod based on axial loads alone. The bending stresses were found to be
about 20% of the overall stress amplitude at the shank center. Other important
observations from stress-time histories of different locations in the connecting rod were
that locations near the oil hole and at the crank end transition have significant
multiaxiality requiring use of an equivalent stress. Also, the R ratio (i.e. minimum to
maximum stress ratio) varies with location and engine speed.

The optimized connecting rod was assumed to be interchangeable with the
existing one. Therefore, the diameters of the crank pin and the piston pin holes, the
overall thickness of the connecting rod, and the crank pin center to piston pin center
distance could not be changed. The piston pin end fits under the piston and is supposed
to clear off the piston skirt and the piston bottom, when in operation. The dimensions of
the bolts and their holes were also retained. Other dimensions of the connecting rod
could be varied, within practical limits. Comparison of FEA results for the existing
connecting rod against the allowable stresses indicated that the shank region of the
connecting rod offers the greatest potential for weight reduction. In the shank region, the
rib and the web thicknesses were reduced, however, only to a certain limit to maintain
forgeability.

The section modulus of the optimized connecting rod should be high enough to
prevent high bending stresses. Bending stresses exist due to inertia forces, and can
also occur due to eccentricities as well as crankshaft and case wall deformations. In
order for the section modulus to be as high as possible, the width of the rib was
increased. After several iterations, which involved determining the loads and performing
FEA for the resulting geometry of each iteration step, an optimized geometry was
obtained, shown in Figure 15. The optimized geometry is based on the use of C70
crackable steel fatigue properties, which are lower than the original conventional forged
steel. In spite of this fact, the mass of the optimized connecting rod is lower than the
mass of the original connecting rod by 10%. This geometry was found to satisfy the
aforementioned design constraints. Maintaining forgeability of the connecting rod was
taken into account during the optimization process. Another aspect addressed to
maintain forgeability is the draft angle provided on the connecting rod surface.

There has been a significant increase in the production of powder metal
connecting rods in North America in the last decade. The main driving force for this
trend has been cost effectiveness of PM connecting rods resulting from near net shape
manufacturing as well as fracture splitting of the cap from the rod. In spite of the
substantially lower weight of the material used, however, the cost of the powder forged
rough stock could be higher than that for the conventional hot drop-forged rough stock,
because of additional operations of powder formation, pre-form formation, pre-sintering,
and sintering (11). Fracture splitting does not require further machining of the matching
surfaces, because fracture faces perfectly fit each other. For the conventional forged
steel connecting rod, the cap and rod are either separately forged, or they are sawed
apart in one-piece forging. In either case, machining of the matching surfaces is required to provide a sound fit of the joint faces. This increases the manufacturing cost significantly. However, with recent introduction of new materials such as C-70 splittable steel, this key advantage of powder metal connecting rods no longer exists, as machining of matching surfaces of splittable steel are no longer required.

Heat treatment, machining of the mating faces of the crank end, and drilling for the sleeve can be eliminated in the manufacturing of the existing forged steel connecting rod by introducing C-70 crackable steel. According to Repgen (12), fracture-split technology as applied to forged steel connecting rod, which is widely used in Europe, cuts the total cost by 25%, compared to the conventional forged steel connecting rod. He also notes that a forged steel connecting rod can run on machining lines originally designed for powder metal connecting rods with a cost reduction of 15%. It should be noted that by using other fracture crackable materials such as micro-alloyed steels having higher yield and fatigue strengths, the weight at the piston pin end and the crank end can be further reduced. Weight reduction in the shank region is, however, limited by manufacturing constraints.

**CONCLUSIONS**

1. Based on the component testing observations, crack growth life was found to be a significant portion of the cast aluminum knuckle fatigue life, while crack growth life was an insignificant portion of the forged steel knuckle fatigue life.

2. Component testing results showed the forged steel knuckle to have about two orders of magnitude longer life than the cast aluminum knuckle, for the same stress amplitude level. This occurred at both short as well as long lives.

3. The S-N predictions for the steering knuckle were overly conservative, whereas strain-life predictions were relatively close to component experimental results. Comparison of the strain-life prediction curves of the components demonstrated that the forged steel knuckle offers more than an order of magnitude longer life than the cast iron knuckle.

4. Forged steel and PM connecting rod tests indicate the forged steel connecting rod exhibits 37% higher fatigue strength, as compared with the powder metal connecting rod. This increased strength results in about two orders of magnitude longer life for the forged steel connecting rod. The difference in fatigue performance between the two connecting rods increases with longer lives.

5. The S-N approach predictions for the connecting rod are reasonable, if the predictions are based on smooth surface finish, rather than forged surface finish. The beneficial compressive residual stresses on the surface nullify the detrimental effect of forged surface finish. Predicted fatigue lives for both forged steel as well as
powder metal connecting rods are mainly within a factor of ±3 of the experimental lives.

6. Manufacturing process considerations, material and cost parameters are major constituents of a general optimization procedure with durability constraints for automotive component. A geometrical optimization without these considerations is not a practical approach for such high volume components.

7. Overall weight and cost reductions of at least 12% and 5%, respectively, are estimated for the forged steel steering knuckle considered, with the cost of the saved material being additional reduction. Due to the small size of the forged steel steering knuckle and many attachment compatibility constraints, only limited changes could be implemented during the optimization process. Components with fewer geometrical restrictions than the steering knuckle considered have much higher potential for weight reduction and cost savings. This, however, require a more detailed design of the component and the suspension system.

8. Fatigue strength was the driving factor in the design and optimization of the connecting rod. The section modulus of the connecting rod should also be high enough to prevent high bending stresses due to inertia forces, eccentricities, as well as crankshaft and case wall deformations.

9. The shank region of the connecting rod offered the greatest potential for weight reduction. The rib and the web thicknesses were reduced, while maintaining forgeability. The optimized geometry is 10% lighter than the current connecting rod for the same fatigue strength, in spite of lower yield and fatigue strengths of C-70 steel compared to the existing forged steel.

10. With using fracture splitting process, the two fracture split parts share a unique surface structure at the fractured surface that prevents the rod and the cap from relative movement, resulting in a firm contact. This increases the stiffness and reduces stress at critical locations in the crank end of the connecting rod. Reduction in machining operations achieved by utilization of the fracture splitting process reduces the production cost by about 25%.

REFERENCES


Table 1: Cost attributes for manufacturing the forged steel steering knuckle.

<table>
<thead>
<tr>
<th>Cost Attributes</th>
<th>General Production Parameters</th>
<th>Forging Process Parameters</th>
<th>Machining Process Parameters</th>
<th>Lubrication Parameters</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Program Line</td>
<td>Annual Prod Volume</td>
<td>Material Cost</td>
<td>Forging Method</td>
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<td>Raw Material Costs</td>
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<td>-</td>
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<tr>
<td>Labor</td>
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<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Tools and Dies</td>
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</table>

Table 2: Summary of the results of optimization stages.

<table>
<thead>
<tr>
<th>Geometry Change</th>
<th>Process Change</th>
<th>Component Weight (kg)</th>
<th>Weight Reduction (%)</th>
<th>Cost Reduction (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>-</td>
<td>2.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stage I</td>
<td>Material removed from body</td>
<td>2.13</td>
<td>9.4</td>
<td>5% more material savings</td>
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<tr>
<td></td>
<td>Hub mounting thickness optimized</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lateral link joint thickness optimized</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stage II Spindle redesigned 2.07 oz | 11.9 oz | 5% + material savings | 2 |

1. Precision forging and warm forging are other proposed process changes for Stage I. These options should be more extensively evaluated in a detailed design stage for their cost impact.
2. Surface enhancement (carburizing, nitriding, hardening) andnode forming compressive residual stresses at surface by surface rolling are proposed additional processes that will reduce component weight by increasing fatigue strength in Stage II. These options should be more extensively evaluated in a detailed design stage for their cost impact.
Figure 1: From left to right the digitized models of the forged steel, cast aluminum and cast iron steering knuckles.

Figure 2: Superimposed stress amplitude versus life curves for forged steel and cast aluminum knuckles.
FIGURE 3: Forged steel connecting rod with a weight of 455 g (Left) and powder metal connecting rod with a weight of 570 g (right).

Figure 4: Experimental stress amplitude vs. cycles to failure for forged steel and powder metal connecting rods.
Figure 5: Superimposed stress amplitude versus life curves based on S-N approach for forged steel, cast aluminum and cast iron knuckles.

Figure 6: Superimposed SWT parameter versus life curves based on strain-life approach for forged steel, cast aluminum and cast iron knuckles.
Figure 7: Effect of surface finish as a function of manufacturing process on fatigue strength (10).
Figure 8: Comparison of predicted and experimental fatigue lives based on S-N approach for the forged steel connecting rod.

Figure 9: Comparison of experimental lives with predicted lives for forged steel and PM connecting rods.
Figure 10: Manufacturing process flow chart for the forged steel steering knuckle.
Figure 11: Forged steel steering knuckle optimization stages followed.

Figure 12: Stage I (left) and Stage II (right) optimized models.
Figure 13: Axial, normal, and the resultant forces at the crank end (a) and at the piston pin end (b) at crank speed of 5700 rev/min.
Figure 14: Stress (von Mises) variation over one engine cycle at 5700 rev/min at locations 9, 12 and 13. XX is the $\sigma_{xx}$ component of stress.

Figure 15: The geometry of the optimized connecting rod.