Simulation based approach for light weighting of Connecting rod by tube hydro forming process

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Abstract. Several attempts have been made to reduce the weight of vehicles in order to increase overall fuel efficiency. Most attempts are focused on the light-weighting of BIW parts. However, very few attempts have been reported on the light-weighting of engine and transmission components. The present study aims at another method of light-weighting and manufacture of the light-weight connecting rod. To reduce the weight of connecting rod a new innovative manufacturing route using tube hydroforming has been proposed. A seamless tube is used as the raw material, which is deformed to its final shape by tube hydroforming. An innovative set of design features were needed for manufacturability using a tube as a raw material. Critical parameters of the solid connecting rod, such as diameters of holes at the big end as well as the small end, and the centre to centre distance, have been maintained equal to the reference solid forged connecting rod. Forming limit diagram has been used to predict the forming safety of the material during the forming process.

1. Introduction
The light-weighting of the automobile leads to improving the fuel efficiency of the vehicle [1]. It can be achieved by innovation in part design or/and part materials. In recent times, these innovations have been used to significantly reduce the weight of the vehicle door, vehicle roof and body in white [2]. However, engine and transmission parts are still mostly made of solid parts and need attention for light weighting. Nayak et al. [3] have manufactured piston from sheet metal process that has 24 percent reduced weight than conventional cast piston having similar performance. Pandey et al. [4] have shown processes to manufacture hollow gear with 32 percent higher specific torque capacity than solid gear. Neugebauer et al. [5] have achieved light weighting by manufacturing near-net-shape hollow rotational-symmetric parts by incremental rolling processes. Thirunavukkarasu et al. [6] have simulated the hydroforming process to produce a hollow crankshaft and obtained an 18 percent reduction in weight. Date et al. [7] have reported an innovative connecting rod manufactured by sheet metal forming processes that has 25 percent lesser weight than forged connecting rod. Moreover, additional advantage of reduction in vibration and noise is also obtained with light weighting of reciprocating engine parts [3].

This light weighting of engine parts with satisfactory performance can be achieved by making hollow parts with appropriate dimensions and material [4]. Different innovative materials and manufacturing processes are used for achieving this [8], [9], [10]. High-strength alloys are used to replace conventionally used steels [11]. This is because high strength alloys can give a similar performance with
less material input. However, these alloys are difficult to deform at room temperature [12]. Hence, hot forming processes is used to obtain the required formability [13], [14].

Hot gas forming is a hot forming process used to form hollow parts with different features [15], [16]. It has been used earlier to achieve near net shape for a part with rotational symmetric and non-symmetric shapes. The major affecting parameters for this process are work piece temperature, gas pressure and compression rate [17], [18]. The preheated workpiece can be used with pressurized hot gas to maintain a high temperature in the workpiece with minimum heat loss. However, proper optimized control of pressure and axial movement are required to achieve thickness control throughout the part [18]. Wu et al. [17] have shown that an optimised pressure should be applied to get required material distribution in part. The compression rate of material should also be optimized as a low compression rate leads to localised thinning in some areas and a high compression rate leads to wrinkling [17].

In the present study, an optimized hot gas forming process has been simulated in AutoForm TubeXpert to manufacture a hollow connecting rod. A high-strength alloy 22MnB5 alloy had been used as workpiece material to be formed at 850°C. The pressure and compression rate have been optimized to obtain the required distribution of the material in the part. The forming limit diagram (FLD) of the material has been used to predict the failure of parts during production. Piercing and hole flanging has been used to achieve the required small end and big end hole dimension. The holes at the two ends are large enough to accommodate a sleeve (bearing bush) in the flanged hole and welded to the flange along the periphery of the sleeve. The bearing bush has an inner diameter such that the outer race of the bearing fits with the same degree of interference as it fits with the forged connecting rod. The thickness of the bearing bush is adequate to support the bearing. Finally, trimming and assembly have been described to obtain the hollow connecting rod.

2. Research methodology and connecting rod profile simulation

In this study, an attempt has been made to design and simulate the process for manufacturing hollow connecting rod (HCR). Figure 1 shows a solid connecting rod used in an engine with the nomenclature of different parts [18]. The present study HCR is designed for Kirloskar Oil Engine Ltd.’s four-stroke, air-cooled and direct injection engine. The dimensional details and working parameters of this engine are given in Table 1. The maximum combustion pressure for the engine is 56.72 bar. The dimensions of the connecting rod currently used for this engine are shown in Table 2.
Table 1. details of the engine for which HCR has been designed.

| Description                  | Details                                      |
|------------------------------|----------------------------------------------|
| Number of Cylinders          | 1                                            |
| Piston Bowl Diameter         | 52 mm (Piston made of Al alloy)              |
| Stroke length                | 110 mm                                       |
| Capacity                     | 661 cc                                       |
| Maximum Power                | 3.5 kW @ 1500 rpm                            |
| Fuel injection Pressure range| 200 tp 250 bar                               |
| Connecting rod length        | 234 mm                                       |
| Connecting Rod mass          | 1.758 kg                                     |
| Rotating Crank radius        | 55 mm                                        |
| Maximum Combustion pressure  | 56.72 bar at 371° and 372° crank angle       |

The HCR designed in the present study aims at reducing the weight of the connecting rod. Furthermore, it also satisfies the dimensional constraints and functional requirements of the connecting rod in the given engine. For the manufacturing of the HCR, the flow chart of the process used is shown in Figure 2. AutoForm TubeXpert simulation module has been used for process simulation. For this process, an annealed hollow tube of 22MnB5 alloy has been used as workpiece material with an initial outer diameter of 22 mm and wall thickness 3 mm. The hot gas forming process has been simulated to perform the forming at 850°C. The mechanical properties of workpiece material at 850°C used for the present analysis are shown in Table 3. The flow stress curve and FLD curve of the material at 850°C as obtained by the AutoForm material library are given in Figure 3 and Figure 4, respectively. The connecting rod has been manufactured in two parts and assembled together. The two parts are connecting rod main body (consisting of the shank, small end and half of the big end) and connecting rod cap. For assembly, two M8 nut-bolts are used. A bush to hold the bearing is peripherally welded to the flange to complete the assembly.

Table 2. Details of the presently used connecting rod dimensions

| Connecting rod part           | Dimension (in mm) |
|-------------------------------|-------------------|
| Big end diameter              | 42.5              |
| Small end diameter            | 10.3              |
| Centre to centre distance     | 239.5             |
| Outer width at big end        | 103.6             |

Figure 2. Flow chart of different processes used in the manufacturing of present connecting rod.

Table 3. Material properties of 22MnB5 at room 850°C

| Mechanical Properties        | Value             |
|------------------------------|-------------------|
| Density                      | 7.68 g/cm³        |
| Poisson’s ratio              | 0.3               |
| Yield strength at 850°C      | 150 MPa           |
| R0                           | 0.7               |
| R45                          | 0.9               |
| R90                          | 0.8               |
| Tensile strength             | 360 Mpa           |
Figure 3. Flow stress of the 22MnB5 at 850°C.

Figure 4. FLD of the 22MnB5 at 850°C.

Figure 5 shows the die setup used for the hot gas forming, hole piercing and hole flanging of the connecting rod main body. Different views of the die setup are shown in Figures 5 (a, b, & c). The tool consists of the central bulging region with an extended main body on both sides. Initially, the workpiece tube of length 500 mm, shown as (d)-(e) in Figure 5, is kept in the die and the die is closed along the parting line. The die's minimum internal diameter is the same as the external diameter of the tube (22mm). Hence, no strain is induced in the workpiece during die closing. The “die inserts” shown in Figure 5 are fixed in the die in the place as shown. The axial tools, schematically shown as nos. 7 and 8 in Figure 5, make contact with the workpiece material. The axial tools are modified to resistance heating electrodes. After that, the tube is filled with pressurized hot gas and axial tools resistance heating is initiated to heat the tube to 850 °C. The pressure map for the bulging is shown in Figure 6. During this process, the axial tools are moved axially towards each other to compress the tube at 2 mm/sec.

After completing the bulging process, the tube's pressure is brought to atmospheric pressure and die inserts are removed. For hole piercing and hole flanging (HPHF) in connecting rod main body, HPHF tool has been used. These tools are designed for piercing and flanging to obtain a set of three flanged holes from the top as well as the bottom of the connecting rod as in Figure 5. The HPHF tool shown in Figure 5 ((1)-(6)) is initially brought in contact with the tube. After that, the pressure inside the tube is increased with hot gas at 850°C and HPHF tools are moved vertically towards the tube axis to achieve piercing and flanging. After completing these processes, HPHF tools are ejected and die is removed. The work piece obtained is quenched to attain high material strength. Thereafter, the workpiece is trimmed to obtain two main bodies of the connecting rod.

Figure 5. Die setup and work piece for forming of connecting rod long main body.
Figure 6. Pressure map used for the hot gas forming process.

The process of manufacturing the cap of the connecting rod involving tube hydroforming followed by piercing and hole flanging has been similarly simulated to obtain two caps, just as a pair of connecting rod main bodies were simulated. Figure 7 (a, b &c) shows the die arrangements used for the simulation of the cap. Figure 7 (d & e) shows the workpiece tube dimension used for the process with a thickness of 3 mm. The initial bulging has been achieved with a pressure map as shown in Figure 6 and with an axial tool compression rate of 2 mm/sec. After achieving the central bulging, gas pressure was removed and the HPHF tools were engaged. After that, the pressure was increased and HPHF tools were inserted to obtain piercing and flanging as obtained for the main body. However, for the manufacturing of connecting rod cap, the HPHF has been designed to achieved a single flanged hole in the middle. Trimming the obtained part produces two connecting rod caps. The connecting rod main body, connecting rod cap, bearing inserts and bolts are assembled to obtain the final connecting rod.

Figure 7. Die setup and work piece for forming of connecting rod cap.

3. Results and discussions
Figure 8 shows the workpiece during the different steps to produce a hollow connecting rod. It shows simulation results at each step for manufacturing the main body as well as the cap. In Figure 8, the colour
code for material failure prediction obtained by AutoForm is shown at the bottom of the figure. Figure 8 (i) shows the initial material after die closing. The grey colour indicates that the material is undeformed. So, it is observed that the material does not get any deformation during die closing.

Figure 8. The forming and assembly steps of hollow connecting rod.
Figure 8 (ii) shows the workpiece on completion of the hot gas forming process. It can be observed that the material is safe and without any localized failure in the central bulge area. None of the elements is in splits, excess thinning or at risk of splits. The I-Beam section of the main body is grey, predicting that the material is undeformated throughout the process. Grey colour is obtained as in the I-Beam region, the outer diameter of the workpiece and inner diameter of the die is same. So there is no deformation in this region. The axial ends of the tube are observed to be a purple colour, indicating thickening in this region. Due to the compressive load from the axial tool, the material gets consolidated at the ends. This leads to thickening in the material.

Figure 8 ((iii) & (iv)) shows the workpiece after piercing (iii), and after flanging operation (iv). Before piercing, the workpiece material is in the same deformed state as obtained after hot gas forming. For the main body, three holes are pierced on the workpiece. One is in the centre region for the big end of connecting rod, and two to obtain the holes for the small end. However, only one hole is obtained in the central bulge region for connecting rod cap workpiece. After achieving the piercing, the flanging tool has been used for flanging the hole. Figure 8 (iv) shows the workpiece obtained after the flanging operation. It can be observed that during the flanging operation, the hole diameter has increased. However, the part is predicted to be safe. The material is free from any localised failures in the material.

After achieving the required shapes by the forming process, the part is trimmed. The trimming is performed along the trimming line shown by the red dotted line in Figure 8 (v). We obtain two connecting rod main body and two connecting rod cap after trimming is completed, as shown in Figure 8 (vi). For the assembly of these parts, M8 bolts are used. The other assembly parts are small end rod bushing, big end bearing inserts, and inclined support for bolts. Hence, following the assembly, two connecting rods are obtained. Figure 8 (vii) shows the final assembly of the hollow connecting rod.

4. Conclusions
A hollow connecting rod production process has been simulated in the present study. Innovative die design and optimized working parameters have been obtained to achieve the required dimension. The following conclusion can be made from this study:

- Using an optimized pressure map and compression rate, required bulging for HCR can be obtained in 22MnB5 material’s tube by hot gas forming process.
- Hole piercing and hole flanging can be used to generate the big end and small end hole dimension with required accuracy.
- The forming limit diagram criteria predicted that no localized thinning or failure is obtained in the material if HCR is manufactured using given process.
- The simulated hollow connecting rod fulfils the critical dimensional requirements, such as, big end diameter, small end diameter and center to center distance.

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