Strength analysis of an aluminium-alloy component of circular geometry developed by cold forming and friction welding method

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To meet the requirements of modern manufacturing of automotive components of near net shape and high strength to weight ratio at lower cost, a 6061Aluminium-alloy bicycle hub (rear) was produced by a newly proposed method combining cold forming and friction welding processes. As the process involved joining of two cold formed halves by friction welding to get the final component (rear bicycle hub), knowledge of the stress distribution over the component under the simulated loading conditions was felt very important to examine its strength. The finite element method, used for the analysis of the component using ANSYS Code, revealed that in the middle portion of the hub-stem (friction welded zone), the stress magnitude is of very low order. The maximum value of stress observed at the junction points of flange and spokes, is within the allowable stress of the material. Thus the structural integrity of the component during use is established.

Keywords: Aluminium-alloy, Cold forming process, Friction-welding process, Strength analysis, Manufacturing
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Introduction

Today’s urgent need for energy saving is motivating rapid innovations in design and manufacturing technology\(^1\) in a wide field of applications ranging from home appliances to automobile and other manufacturing sectors. Such innovations necessarily involve changes in materials selection and improvements in both materials properties and manufacturing processes. In recent years, there is an increasing trend worldwide, particularly in automotive sectors, to manufacture light engineering components of near net shape with: i) Minimum metal consumption; ii) High strength to weight ratio; iii) Excellent surface finish to avoid final machining; iv) Greater mechanical properties due to more favourable grain-orientation; v) Rapid rate of manufacturing; and vi) Lower cost of production. Notable among the trend is the increasing use of aluminium alloys (Al-alloys) in automotive sectors\(^7\). In many cases, steel is being replaced with Al-alloys to obtain high strength to weight ratio of the component.

Conventional manufacturing processes\(^3\), which are mostly followed now a days, are: A) **Traditional Machining Processes**, involving a lot of successive operations like turning, milling, boring, grinding etc. for complete manufacturing of a component out of a large sized stock material; B) **Non-Traditional Machining Processes**\(^5\) [i) Electrochemical Machining (ECM); ii) Electrical Discharge Machining (EDM), Abrasive Jet Machining (AJM); iii) Magnetic Pulse Forming (MPF); iv) Laser Beam Machining (LBM); and v) Electron Beam Machining (EBM)]; C) **Precision Casting Methods**\(^5\) [i) Gravity Die Casting; ii) Pressure Die Casting; iii) Squeeze Casting\(^6\) etc]; and D) **Metal Forming Processes**\(^3\) [i) Hot Forming at a temperature above the re-crystallization temperature of the metal being deformed; ii) Cold Forming at the meta-stable range of the metal at slightly below re-crystallization temperature; and iii) High Energy Rate Forming or Explosive Forming]. In addition, a new method of producing components of complex design and intricate shape has come out now a days, which is better known as **Rapid Prototyping (RP)** and **Investment Casting**\(^8,9\) route of component manufacturing.

All these methods have both merits and demerits, but none of them can meet all the requirements of modern manufacturing like: i) Near net to net shape production; ii) Minimum metal consumption; iii) Extremely high mechanical properties; iv) High density and surface finish; and v) High rate of production with minimum cost. The proposed new technique is to reduce the cost of production, upgrade the quality and mechanical properties of the product and manufacture of almost net shape components.

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directly from the stock having the same volume to that of the final product (Fig. 1). A bicycle hub has been developed by this method to examine suitability of the proposed method using 6061 Al-Alloy. The process, involved joining of two matched halves by friction welding (parent metal to parent metal joining) to get the final component (6061Al-alloy bicycle rear hub). To examine stress distribution over the component under the simulated loading conditions, finite element analysis of the rear bicycle hub component of Al-alloy was carried out. Strength analysis under the application of suitable load has been done and the stresses and deformation have been obtained accordingly. ANSYS code has been used to analyze the component.

Proposed Manufacturing Process

Cold Forming (CF)\(^{10}\) at room temperature assisted by Friction Welding (FW)\(^{11}\) may be an ideal combination for manufacturing of a net shape component of outstanding mechanical properties, good surface quality and lower cost of production. CF process may be treated as a method of manufacturing a component by forming a billet of predetermined size and shape (having the same volume to that of the final component) within a closed die at room temperature. The process may be carried out in different steps involving i) intermittent annealing and ii) zinc-phosphating and lubrication before each step of forming operation. Intermittent annealing eliminates the effect of strain-hardening introduced during cold deformation in the previous step and to increase the ductility of the material so that a lower load is required for the same amount of deformation. Zinc-phosphating and lubrication of the billets is required to minimize the frictional conditions at the die-metal interface.

Although axisymmetric components are particularly suited for CF operation, the process have got some limitations in manufacturing certain components like bicycle hub, tricot warp beam etc, having circular flanges at both ends. In proposed method, problem was overcome by splitting the component into two portions, each being developed separately from their respective initial billets by CF and finally joined by FW process\(^ {12}\) to get the desired full component. Since FW of similar metals is associated with parent metal to parent metal joining and as no filler metal is used in this case, the integrity of the component is not disturbed from the material point of view and an uniform mechanical properties throughout the body of the component can be achieved by post heat treatment of the friction welded part\(^ {13}\). After final heat treatment, a uniform hardness contour within 96-100HB was achieved across the stem and flange portions of the hub.

Manufacturing Technology

Since a bicycle hub has circular flanges at both ends, it cannot be taken out of the die, as a whole, very easily after forming operations. In the present work, after estimation of volume, size and shape of the initial billets required for each part were annealed at 415°C, zinc phosphated in a suitable zinc-phosphating bath and lubricated in alkaline soap solution in order to minimize the frictional conditions at the die-metal interface (Fig. 2). Each part was then cold formed separately in a 100 ton hydraulic press in two steps and finally joined by friction welding process to get the full component, which after heat treatment (full annealing at 440°C followed by solution treatment at 530°C and ageing at 175°C for 8h) showed almost similar mechanical properties (Table 1) to that of the parent metal in heat treated

<table>
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<tr>
<th>Table 1—Comparative statement of mechanical properties of parent metal and friction welded metal in heat treated (T6) condition</th>
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<tr>
<td>Mechanical properties</td>
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<tr>
<td>Tensile strength, Mpa</td>
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<tr>
<td>Yield strength, Mpa</td>
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<tr>
<td>Hardness, HB</td>
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<td>% Elongation</td>
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Annealing of billets of pre-determined size and shape, at 415°C (Temper-O) Material: 6061 Al-Alloy

Zinc-Phosphating and Lubrication of billets.

Fabrication of Die(s) & Punch(es). Material: Cold-Work Die Steel (AISI/D2-Grade)

Heat-Treatment to impart the required mechanical properties to the finished component (Temper-T6)

Friction Welding of two matching hubs in a 12Ton Friction Welding machine (continuous type)

2-step cold forming in a 100 Ton Hydraulic Press. Load: 20 - 60T Condition: Room Temp.

Fig. 2—Process flow diagram for manufacturing of Al-alloy bicycle hub (rear) by the proposed method

Fig. 3—Finite element mesh of bicycle rear hub

condition. The resultant component was of near net shape. A little machining on the external surface of the component was done to get the final luster. A large number of parts were fabricated by the proposed method for various testing and inspection, which also ensured repeatability of the process.

Strength Analysis

Finite Element Model

Based on dimensions obtained from engineering drawing, geometry of the part was idealized by supressing fillets and small diametral variations at different sections of the hub. Due to symmetry of the hub structure only one-half portion was idealized (Fig. 3). Eight nodded shell elements having six degrees of freedom per node have been used for discretization of the model. Following material properties of Al-alloy (6061Gr.) were considered: Modulus of elasticity, $0.68 \times 10^5$ MPa; Poisson’s ratio, 0.33; Density, 2691 kg/m$^3$; Yield stress, 276 MPa; and Allowable stress, 92 MPa (considering factor of safety=3). The physical properties of the material after joining and subsequent heat treatment are considered to be same as has been observed through experimentation (Table 1).

Load

Load of rider on the bicycle is distributed to front and rear wheels through frame, axles, bearings and hub etc. To evaluate stress distribution on both front and rear hub, a vertical load of 1000N was applied on each hub through the bearings. The loads at different locations of the hub, transmitted through the bearing balls, are different at different points of the hub and are evaluated from the following relation:

$$Q_{max} = \frac{4.37 \times Fr}{Z}$$

$$Q_{y} = Q_{max} (\cos \psi)^{1.5}$$

where, $F_r$ = Radial load on each side of the


\[ \psi = \frac{1000}{2} = 500N; \]

\[ Z = \text{Number of balls in the supporting bearing}; \]

\[ Q_{max} = \text{Maximum load on a ball}; \]

\[ \Psi = \text{Position angle of balls with respect to maximum loaded ball}; \]

\[ Q_{\psi} = \text{Radial load at position angle } \Psi \text{ on the hub inner surface} \]

The locations of the balls change with rotation of the bearing. The magnitudes and positions of the load also change accordingly. The most critical loading condition is used in the analysis. In normal bicycle, double row ball bearings with 9 balls in each row, are used. So, with \( Z = 9 \), values of \( Q_{\psi} \) combined for both the rows (Table 2). Obviously, the upper portion of the hub is not subjected to any load and bottom most ball is subjected to minimum load. Evaluated loads have been applied in radial direction at the appropriate nodes. Stresses and deformations have been obtained by constraining the nodes at the spoke location in the radial directions. Output stress values can be multiplied by suitable magnification factor to evaluate the stress on the hub corresponding to possible maximum loads.

\section*{Results and Discussion}

As Von-Mises stress \( (\sigma_{eq}) \) under multiaxial stress condition (Fig. 4) is a good measure of stress condition in a component, the same has been used for detail analysis.

\[ \sigma_{eq} = \sqrt{\frac{1}{2} \left( \sigma_1 - \sigma_2 \right)^2 + \left( \sigma_2 - \sigma_3 \right)^2 + \left( \sigma_3 - \sigma_1 \right)^2} \]

It is observed that the stresses induced are very localized in nature and confined only in the zones of support locations and load application areas. The maximum value of stress magnitude is of the order of 62.67 MPa (Fig. 5). In the middle portion of stem of the hub (at friction welded zone), stress magnitude is of the order of 12 MPa. In order to examine the strength of the component, maximum possible load on the hub has been estimated to be 1500N considering the weight of a pillion rider (800N), half of weight of the rider (400N) and additional weight of 300N. The maximum stress is thus 78.85 MPa, which is less than the allowable stress (92 MPa) of the material. Maximum deformation is only 0.03 mm. The overall stress distribution and magnitude, thus, ensures the strength of the component under the possible loading condition.

\section*{Conclusions}

The results of Finite Element Analysis of 6061 Al-alloy bicycle hub, produced by the combined processes of cold forming and friction welding, revealed that in the middle portion of the hub-stem (friction welded zone), stress magnitude is of very low order. The maximum value of stress observed at the junction points of flange and spokes under the

\begin{table}[h]
\centering
\caption{Loads on each side of hub (for \( F_r = 500N \))}
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
\( \psi \) (deg.) & 0 & 40 & 80 & 120 & 160 & 200 & 240 & 280 & 320 \\
\hline
\( Q_{\psi} \) (N) & 242.78 & 162.78 & 17.57 & 0 & 0 & 0 & 0 & 17.57 & 162.78 \\
\hline
\end{tabular}
\end{table}
simulated loading condition, is within the allowable stress of the material. Thus, the proposed method, combining CF and FW, can be effectively used for the near net shape manufacturing of axisymmetric components having circular flanges on both ends.

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