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Development of a Manufacturing Process for High-Power-Density Hollow Shafts

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Presentation Outline

1. Introduction
2. Research objectives and approach
3. Proposed forging sequence for hollow shaft
4. Finite element analysis of the proposed sequence
5. Experimental validation
6. Concluding remarks
Research objectives

The overall objective of this study is to develop a cost-effective manufacturing process for high-power-density hollow shafts. The specific objectives are to

(a) Develop a forming sequence for producing a flange along a hollow shaft by utilizing differential heating techniques.

(b) Carry out economic analysis with focus on the architecture of forming sequences and hollow billet production.

(c) In collaboration with a forging company, a tube manufacturer and heat treatment company build a demonstration test setup.
Manufacturing Process for Hollow Shafts
- Approach and Key Strategies -

1. Employ existing forging technologies
2. Employ forging machine architecture
3. Employ induction heating technologies
4. Comparable cycle time to forging

Conventional forging of axle shafts

https://www.sypristechnologies.com/products
Proposed forging Process based on Differential Heating Concepts

**Type I**
- I. Induction heating
- II. Upsetting
- III. Coining
- IV. Flanging

*The tubular billet is used as a pseudo die*

**Type II**
- I. Induction heating
- II. Upsetting
- III. Coining
- IV. Flanging

*The tube is gripped during forging*

**Type III**

Hybrid (A combination of Type I and Type II)
Proposed forging Process based on Differential Heating Concepts

- **Nosing**: A step and a taper are cold forged. The step reduces the load exerted on cold material (pseudo die). The taper facilitates easy ejection and suppresses wrinkling.

- **Induction heating**: The workpiece is selectively heated.

- **Upsetting**: The central hole is filled and a solid section is obtained.

- **Coning**: The solid section is shortened and widened. Coning prevents buckling and allows the material to flow concentrically.

- **Flanging**: The flange is created.
Finite Element Simulations of the Proposed Progressive Sequence
FE Simulations for various hollow shafts

Material: AISI 1045

Dimensions of initial stock:
- OD = 0.5 in (12.6 mm)
- ID = 0.26 in (6.6 mm)
- Length = 6.5 in (165 mm)

Dimensions of the final part:
- Flange OD = 3 in (76 mm)
- Thickness = 0.25 in (6.4 mm)
- Length = 2.3 in (58 mm)

Laboratory scale for experimental validation

Axle shaft

Mainshaft

Pinion gear shaft
FE Simulation (Nosing)

Assumption:
- The workpiece is rigid-plastic and the die is rigid.

Modeling: (DEFORM)
- OD increases by 31 % (from 12.7 mm to 16.7 mm).
- Height reduction is 27 % (from 124 mm to 90 mm).
- Tapered angle is 1.3 deg.

Mesh setting:
- Element size : 0.3 mm

Remesh setting:
- Interference depth = 0.1 mm or every five steps

Workpiece-die friction:
- Shear friction factor = 0.3

Nosing can be carried out cold or hot *
FE Simulation (Upsetting to create a solid section)

FE Modeling: (DEFORM)

Workpiece-die friction:
- shear friction factor $m = 0.5$ (for hot die-workpiece interface)
- $m = 0.12$ for cold die-workpiece interface)

Workpiece-die heat transfer
- Heat transfer coefficient = 11 N/sec/mm/C

Hot (900 C)
Cold
FE Simulation (Coning and Flanging)

FE Modeling:
- OD increases by 50 \% (from 16.7 mm to 25 mm).
- Height reduction is 46 \% (from 44 mm to 21 mm).
- Tapered angle is 4 deg.

FE Modeling:
- The flange thickness is 6 mm.

Coning Operation

Flanging Operation
FE Simulation Results
(Effective Strain Distribution)

Maximum strain after the nosing stage is 1.84 and it occurs at the step.

Maximum strain after the upsetting stage is 4.06 and it occurs along the center line.

Maximum strain after the coning operation is 4.74.
The maximum strain of 7.28 occurs at the center of the flange.

The material in the transitional region yields by a small amount. The strain ranges from 0.7 to 2.4.

The cold section does not yield.

No defect occurs, however, there is strain concentration at the middle of the flange.
FE Simulation Results for Lab scale size OD=0.5”
(Forging Load)

<table>
<thead>
<tr>
<th>Process</th>
<th>Load (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nosing</td>
<td>25 tons</td>
</tr>
<tr>
<td>Upsetting</td>
<td>21 tons</td>
</tr>
<tr>
<td>Coning</td>
<td>19 tons</td>
</tr>
<tr>
<td>Flanging</td>
<td>48 tons</td>
</tr>
</tbody>
</table>

Maximum load
Forging of Hollow Mainshafts from Tubes

Conventional Forging of Gear Box Mainshaft

Induction Heating

Warm
Cold
Hot

Unit: mm

Strain

6.39
4.26
2.13
0.000
Forging of Hollow Pinion Gear Shafts from Tubes

Conventional Forging of Pinion Gear Shafts

I. Extrusion
II. Induction Heating

- Warm
- Cold
- Hot

Strain

Unit: mm

0.90
27.43
20
174
0.50
0.32
Experimental validation
## Experiment Setup (Specimen and Equipment)

### Specimen

<table>
<thead>
<tr>
<th></th>
<th>Group S (short)</th>
<th>Group M (medium)</th>
<th>Group L (long)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>AISI 1020</td>
<td>AISI 1020</td>
<td>AISI 1020</td>
</tr>
<tr>
<td>ID (in)</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>OD (in)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>L (in)</td>
<td>3.9</td>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>L/OD</td>
<td>7.8</td>
<td>10</td>
<td>13</td>
</tr>
</tbody>
</table>

### Equipment:

- A 150 ton hydraulic press
Experiment Setup
(Heating of the tubular sample and die pre-heating)

The Induction Heater is used to preheat the specimen.
Specification:
  • Frequency: 0-30 KHz
  • Power: 15 kw

The Band Heater is used to preheat the die.
Specification:
  • ID = 2.75 in or 3 in
  • Width = 1.5 in or 2 in
  • Power = 400 W
  • Maximum temperature: 600 °C

The electrical furnace is used for die preheating as well.
Specification:
  • Power = 1000 W
  • Maximum temperature: 1200 °C
The die case, inserts and the punch are preheated with the band heater to 200 °C. Taper die and split inserts are used for easy ejection.
Tooling Design for Coning Operation

The top die is preheated (200°C) with the band heater and aligned with the bottom die. The cap is preheated in the furnace to 200 °C. Then the workpiece is shaped as the top die moves downwards.
Experiment Results
(Preforms and final parts)

I. Nosing 1  II. Nosing 2  III. Upsetting  IV. Coning  V. Flanging
Experimental Results
(Formed hollow shafts _ laboratory scale )

Dimensions after Flanging (inch)

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>M</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1.76</td>
<td>1.9</td>
<td>1.97</td>
</tr>
<tr>
<td>t</td>
<td>0.19</td>
<td>0.33</td>
<td>0.29</td>
</tr>
<tr>
<td>OD1</td>
<td>1.37</td>
<td>1.36</td>
<td>1.38</td>
</tr>
<tr>
<td>OD2</td>
<td>0.505</td>
<td>0.501</td>
<td>0.51</td>
</tr>
<tr>
<td>ID</td>
<td>0.256</td>
<td>0.24</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Concluding Remarks

A differential heating based process is presented to produce hollow shaft using a tubular body as the initial stock. This process is divided into five stages:

i) nosing, ii) induction heating, iii) upsetting, iv) coning and v) flanging.

The nosing operation is used to cold forge a step on the shaft body, which prevents buckling and overload of the cold section. The induction heating selectively heats the forming zone. The upsetting stage is used to fill the central hole. The coning and flanging stages are used to create the conical head and the flange.

- The experimental results demonstrate that the proposed process is feasible to hollow power transmission shaft. The cold section remains un-deformed and hollow.
- FEA shows that the formed axle shaft exhibits a maximum strain of 7.28, which occurs at the center of the flange.
Concluding Remarks

- There were some differences between the loads obtained from the FE simulations and experiments which were attributed to
  - (a) heat loss as the process was carried out using a low speed hydraulic press
  - (b) the experiments were run dry (without lubricants), resulting in higher friction load.
Acknowledgments

- SFTC for providing the DEFORMN2D software for the induction heating simulation.
- FIERF for funding the project.
- Mid-West Forge for participating in this project
- Mr. John Walters for advising NCSU on forging technologies
Thanks for listening!