Upsetting of bi-metallic ring billets

K. Essa a, I. Kacmarcik b, P. Hartley a, M. Plancak a,∗, D. Vilotic b

a University of Birmingham, United Kingdom
b University of Novi Sad, Faculty of Technical Science, Serbia

ARTICLE INFO

Article history:
Received 22 July 2011
Received in revised form 10 October 2011
Accepted 6 November 2011
Available online 12 November 2011

Keywords:
Upsetting
Bi-metallic
Experiment
Finite-element modelling

ABSTRACT

This report examines the behaviour of bi-metallic components during the cold upsetting process. Each component consists of a solid inner cylinder around which is fitted a ring of a different material. In the first case experimental studies are conducted of a ring of mild steel C45E material surrounded by a softer C15E core. These tests are used to validate the finite-element models. The finite-element method is then used to extend the initial tests to a wider range of cylinder and ring geometries. It is also used to explore a second case where the materials are reversed to give a bi-metallic component with a stronger core. The principal objective is examine how contact between the inner cylinder and outer ring is maintained during the upsetting process. It is apparent that the geometries of the two component parts of the billet are the dominant factors affecting deformation, as the influence of changing the material has only a very small effect. With an initial height/outter diameter ratio of 1.5, contact at the cylinder/ring interface is maintained over the most of the initially contacting surfaces. A small cavity is formed when the inner/outer ring diameter reaches 0.6. Above this value the cavity will become larger, and at 0.8 the wall thickness is sufficiently thin to allow a double-barrel outer profile to develop with two cavities. With an initial height/outer diameter ratio of 1.0 or less, the formation of interfacial cavities is much less and demonstrates the viability of producing bi-metallic components in this way.

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1. Introduction

The forming of two different metallic materials in a single forming operation is well established in processes such as rod and tube extrusion and sheet rolling. All these processes induce a substantial and consistent compressive state of stress between the two materials so that the interface maintains intimate contact and ensures an effective bond. Such a feature is essential, as shown for example in the work by Pan et al. (2006) in clad sheet rolling, by Kazanowski et al. (2004) in rod extrusion and by Mamalis et al. (2006) in tube extrusion. In both extrusion and rolling the pressure applied to the material will be normal to the interface, ensuring its compressive nature. In the upsetting process considered here, of bi-metallic ring billets, where a ring of one material is closely fitted around a solid cylinder of another material before upsetting, the load is applied to the billets parallel to the plane of the interface so that while under some conditions the pressure at the interface will be compressive, this may not always be the case and tensile loads may also be generated resulting in local separation of the two surfaces. It is this difficulty that has prevented the open die forging of bi-metallic products becoming more widespread. There is very little active research in this area, although some work has been performed by Domblesky and Kraft (2007) on bi-metallic billets where the billet consists of two cylindrical specimens in which one is placed on top of the other. When compressed axially, this, as in the case of rolling and extrusion, provides a compressive state at the interface, very similar to friction-stir welding as shown by Zhang and Zhang (2009), where the compression is accompanied by additional shear. Yang et al. (2010) have examined the thixo-forging of two bi-metallic composites. The focus of this closed-die, high temperature forging centred on the nature of the metallurgical bond between the two component materials. Behrens et al. (2008) examined hot forging of helical gears and shafts in a process described as compound forging. In this case two materials were welded together to form the forging blank, deformation during the process then produced a component with a hard, wear-resistant surface layer with a more ductile inner bulk material. The authors suggested that this structure provided an improved load-adapted distribution of material. Leitão et al. (1997) examined deformation in the forming of bi-metallic coins, a process with some characteristics similar to that considered in the present work. They used a finite element model to investigate the bi-metallic forming of coins produced from copper–zinc and copper–nickel alloys. But once again it is clear that in coining operations such as this, where the two blanks that comprise the billet are held in a closed die, it ensures

∗ Corresponding author at: Faculty of Technical Science, Trg Dositeja Obradovica 6, 21000 Novi Sad, Serbia. Tel.: +381 21 485 2337; fax: +381 21 454 495.
E-mail address: plancak@uns.ac.rs (M. Plancak).

0924-0136/ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2011.11.005
that as material from the inner blank spreads out to fill any depression in the outer coin rim, a mechanical bond is developed with the rim under the action of compressive forces. Such coins and medallions have been produced for centuries but little recorded scientific research on the process exists. In a rather different approach Schlemmer and Osman (2005) investigated the influence of differential heating during the upsetting of bi-metallic solid and hollow billets consisting of aluminium and copper. The localised heating caused exaggerated bulging at the mid-height but in all cases no separation of the interface was apparent.

This paper presents both experimental and finite-element studies of the cold upsetting of bi-metallic ring type billets to address the question of whether such a process is viable. In this process there is no attempt to provide a mechanical, welded or metallurgical bond between the two materials. Any resulting bond must rely entirely on the deformation mechanics during the process. The focus in the current study is on the influence of the relative geometry of the two components comprising the bi-metallic billet and attention is given to the extent of the relative contact between the two materials that is maintained during the upsetting process. The results will assist in determining the scope for cold forging of bi-metallic preforms with no pre-process interface bond.

2. Initial experimental data

In the initial experimental observations, the billets consist of an outer ring which is fitted around a solid cylinder, as shown in Fig. 1.

In these experimental trials, the material of the inner cylinder was mild steel C15E, with a stress–strain curve in the form:

\[ K_1 \text{ (MPa)} = 276.44 + 397.715 \psi^{0.317} \]

The outer ring was made of a stronger material, C45E, whose stress–strain curve has the form:

\[ K_2 \text{ (MPa)} = 289.68 + 668.78 \psi^{0.3184} \]

In all tests the outer ring was a close fit over the inner cylinder. Mineral oil was applied as a lubricant to the end faces of the billets prior to deformation. The close fit of the two parts prevented any lubricant entering the cylinder–ring interface. For this combination of material and lubricant the coefficient of friction was evaluated by Kačmarčík et al. (2011) using a standard ring test and estimated to be 0.11. All experiments were performed using a hydraulic Sack and Kiesselbach press of 6300 kN capacity (see Fig. 2). Billets were compressed using flat platens of alloyed steel, hardened to 63 HRC. The stroke was measured by an inductive HBM sensor, type W50

and force by HBM sensor P3M. All tests were conducted with a platen velocity of 0.06 mm/s.

Three different geometries were considered in the experimental investigation. The initial and final dimensions (after deformation) of each specimen are given in Table 1. The strain recorded in Table 1 (and also in Table 2), is included as representative of the average axial compression, determined from strain = \( \ln(H_0/H_1) \).

Photographs of each specimen before and after deformation, are shown in Fig. 3.

After compression each bi-metallic billet was cut along a vertical meridian plane in order to determine the amount of relative contact between the two billet components. Fig. 4 shows the two parts of a billet after cutting and separation. The more pronounced mid-height surface bulge typical of the inner solid cylinder is clearly

**Fig. 1.** Initial (a) and final (b) dimensions of specimen.

**Fig. 2.** A typical compression test in process.

**Fig. 3.** Initial and compressed billets.
Table 1
Initial and final dimensions.

<table>
<thead>
<tr>
<th>Billet number</th>
<th>Initial dimensions (mm)</th>
<th>Final dimensions</th>
<th>Position of no contact area (mm)</th>
<th>Load at the end of the process (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_0$</td>
<td>$D_0$</td>
<td>$d_0$</td>
<td>$H_1$</td>
</tr>
<tr>
<td>1a</td>
<td>60.18</td>
<td>39.98</td>
<td>23.97</td>
<td>37.64</td>
</tr>
<tr>
<td>1b</td>
<td>60.14</td>
<td>39.97</td>
<td>24.01</td>
<td>32.53</td>
</tr>
<tr>
<td>2</td>
<td>39.32</td>
<td>40.01</td>
<td>23.97</td>
<td>21.16</td>
</tr>
<tr>
<td>3</td>
<td>14.20</td>
<td>39.90</td>
<td>24.00</td>
<td>9.30</td>
</tr>
</tbody>
</table>

Table 2
Finite-element data and comparison of contact lengths.

<table>
<thead>
<tr>
<th>Model</th>
<th>Height, $H_0$ (mm)</th>
<th>Outer ring dia., $D_o$ (mm)</th>
<th>Inner ring dia., $D_i$ (mm)</th>
<th>Experimental contact length from one surface, $L_{exp}$ (mm) (average)</th>
<th>FE contact length from one surface, $L_{fe}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strain $\sim$ 0.5</td>
<td>Strain $\sim$ 0.65</td>
</tr>
<tr>
<td>1a</td>
<td>60</td>
<td>40</td>
<td>24</td>
<td>9.5</td>
<td>–</td>
</tr>
<tr>
<td>1b</td>
<td>60</td>
<td>40</td>
<td>24</td>
<td>–</td>
<td>9.6</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>40</td>
<td>24</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>40</td>
<td>24</td>
<td>No cavity</td>
<td>–</td>
</tr>
</tbody>
</table>

displayed. The outer profile of the solid cylinder (or the corresponding inner profile of the ring) is very similar to the internal deformation that would be seen in a completely solid cylinder at a similar radius.

On the meridian cross section of the specimen, cavities (regions of no contact between the two components) could be detected. The distance of the initial points of separation of these channels in relation to the upper and lower surfaces of the specimen is given in Fig. 5 and also listed in Table 1. Also given in Fig. 5 is the load–stroke diagram for each test. For specimen No. 3, the shortest specimen, full contact was maintained, in the other three tests a mid-height cavity is clearly visible. In each of these cases the average distance from the upper or lower surface to the initial point of separation shows little variation, being between 9 and 10 mm.

3. Finite element models of experimental tests

The experimental data provides some initial insight into the interaction between the solid cylinder and its outer ring, but as the data is limited, further analyses will be conducted using a finite-element model. Initial validation of the finite-element models is assessed by comparison to the experimental data.

3.1. Finite element data

All the analyses are performed using Abaqus/Implicit, with the models using a fine mesh consisting of 8-node quadratic axisymmetric elements with reduced integration, CAX8R. In each FE model a friction coefficient of 0.11 at the model/platen interfaces is specified, with zero friction assumed at the cylinder/ring interface. In both locations, surface to surface contact is assumed. All models are axisymmetric with nodal points on the left-hand edge constrained to move along the central axis. Due to symmetry only one half of the work-piece cross section is required in the model. The upper rigid platen translates vertically down imposing deformation on the model which rests on a rigid, stationary, lower platen. The FE predictions of the deformed models are shown in Fig. 6. Table 2 shows the model dimensions, corresponding to the experimental data, and the extent of contact between the cylinder and ring.

In all cases the external profiles are very similar to those observed experimentally, with the tallest model having the greatest radius of curvature. For model 1, the distance to the point of cavity formation is overestimated at a strain of 0.5, but corresponds within 1% at a strain of 0.65. For model 2 a smaller cavity is indicated in both the experimental and the FE data, although the latter suggests a greater amount of separation. For model 3 the results are very similar. In each case the load–displacement data in Fig. 7 indicates a good correlation between experiment and FE. The profile of the load–displacement characteristic is similar in all cases although the FE results show a small underestimation of the experimental loads. The correlation is sufficient to provide confidence in the extended FE modelling data.

3.2. Influence of interface contact friction

It is not possible to determine precisely the experimental frictional conditions that exist at the contact interface between the inner and outer rings, hence the assumption of zero friction in the preceding models. To assess the importance of the contact friction a number of additional simulations were performed with a friction coefficient ranging from 0 to 0.5. The geometry of model 1 (initial height 60 mm, outer diameter 40 mm, interface diameter 24 mm) was used as the test example. Fig. 8 shows the extent of deformation predicted at the end of the axial compression process (equivalent to an average compressive logarithmic axial strain of 0.65). The general pattern of deformation for each level of cylinder–ring interface friction shows very little variation. As may be expected, there appears to be less interfacial sliding with higher levels of friction, resulting in less separation from the platens of the upper edge of the ring at its inner radius. Although the amount of cylinder–ring interfacial separation is difficult to see through a simple visual inspection, if the extent of cylinder–ring interface contact is carefully checked a clearer effect is apparent. Fig. 9 shows that
an increase in interface friction will increase the surface contact, and of course further increase the effect of friction in reducing any interfacial sliding. The cavity formed as the two surfaces separate increases until the coefficient of friction reaches 0.4, at which level any separation is negligible. The experimental measurement shows an average extent of contact from the platens of 9.6 mm, compared to 9.5 mm for zero friction, 9.44 mm for friction of 0.01 and 9.71 mm for friction of 0.05. The amount of contact increases more rapidly as once the coefficient of friction reaches 0.1. It is therefore a reasonable assumption to use zero friction at the interface for the finite-element models.

4. Extended finite-element modelling

To investigate a wider range of geometric effects on billet deformation, further cylinder/ring combinations were analysed. The platen contact friction is again 0.11, while zero friction is used at the ring–cylinder interface. In addition, two cases where the inner
Table 3

Finite element models.

<table>
<thead>
<tr>
<th>Model (equivalent expt.)</th>
<th>Height, ( H_e ) (mm)</th>
<th>Outer ring dia., ( D_o ) (mm)</th>
<th>Inner ring dia., ( D_i ) (mm)</th>
<th>( H_o/D_o )</th>
<th>( D_i/D_o )</th>
<th>FE contact length, ( L_o ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>60</td>
<td>40</td>
<td>16</td>
<td>1.50</td>
<td>0.4</td>
<td>15.7*</td>
</tr>
<tr>
<td>B</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td>1.50</td>
<td>0.5</td>
<td>13.9</td>
</tr>
<tr>
<td>C (1b)</td>
<td>60</td>
<td>40</td>
<td>24</td>
<td>1.50</td>
<td>0.6</td>
<td>9.46</td>
</tr>
<tr>
<td>D</td>
<td>60</td>
<td>40</td>
<td>28</td>
<td>1.50</td>
<td>0.7</td>
<td>7.0</td>
</tr>
<tr>
<td>E</td>
<td>60</td>
<td>40</td>
<td>32</td>
<td>1.50</td>
<td>0.8</td>
<td>4.1</td>
</tr>
<tr>
<td>F (2)</td>
<td>40</td>
<td>40</td>
<td>24</td>
<td>1.00</td>
<td>0.6</td>
<td>7.3</td>
</tr>
<tr>
<td>G (3)</td>
<td>14</td>
<td>40</td>
<td>24</td>
<td>0.35</td>
<td>0.6</td>
<td>3.7*</td>
</tr>
<tr>
<td>H</td>
<td>20</td>
<td>40</td>
<td>24</td>
<td>0.50</td>
<td>0.6</td>
<td>5.2*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (equivalent expt.)</th>
<th>Height, ( H_e ) (mm)</th>
<th>Outer ring dia., ( D_o ) (mm)</th>
<th>Inner ring dia., ( D_i ) (mm)</th>
<th>( H_o/D_o )</th>
<th>( D_i/D_o )</th>
<th>FE contact length, ( L_o ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>60</td>
<td>40</td>
<td>24</td>
<td>1.50</td>
<td>0.6</td>
<td>8.26</td>
</tr>
<tr>
<td>J</td>
<td>60</td>
<td>40</td>
<td>24</td>
<td>1.50</td>
<td>0.6</td>
<td>–</td>
</tr>
</tbody>
</table>

* Full contact, i.e. no cavity.

and outer materials were the same were investigated and compared to models of solid cylinders of the same external geometry. All dimensions are shown in Table 3.

The deformed components at the end of the upsetting process for models A–H, are shown in Fig. 10.

To investigate the influence of material properties, the materials were reversed so that the stronger material formed the inner solid cylinder and the weaker material the outer ring. The deformation pattern in this case is shown in Fig. 11.

For comparison, two cases were examined (models I and J) in which the same material is used for both the inner cylinder and the ring. The initial height/outer diameter ratio is 1.5 and the ratio of inner to outer ring diameter is 0.6. The deformation patterns at an average axial strain of 0.65 are shown in Fig. 12.

The results of simulating upsetting with solid cylinders of a single material are shown in Fig. 13. In both cases the initial height/outer diameter ratio is 1.5. As may be expected the external profile is more similar to that of the bi-metallic models when the inner/outer diameter ratio of the latter is small (e.g. 0.4 or 0.5). As the outer ring reduces in thickness there is a greater difference. When considering the solid cylinders only, the weaker material, C15E, shows a very slightly smaller curvature than the stronger C45E material.

The results in Fig. 12, for the cases where the cylinder and ring are of the same material, show that the deformation is not the same as that for a completely solid cylinder of the same external geometry, as shown in Fig. 13. There is a clear area of interfacial separation, as a result of the two components trying to deform in different modes, as in the bi-metal examples, which suggests that the geometry of each component is a critical factor in determining the deformation behaviour.

5. Evaluation of deformation behaviour

5.1. Inner material C15E, outer material C45E

The deformation patterns in Fig. 8 show that for an intermediate inner/outer diameter ratio (e.g. models A, B, G, H) the bi-metallic
Fig. 8. Deformation behaviour for various coefficients of friction at the ring–cylinder interface (geometry based on model 1b).

Fig. 9. Influence of the coefficient of friction at the cylinder–ring interface on the extent of interfacial contact, based on finite element data (♦). The broken line superimposed on the figure indicates the contact measured experimentally (geometry based on model 1b).

Fig. 10. Deformed components, inner material C15E, outer material C45E.

Fig. 11. Deformed components, inner material C45E, outer material C15E.
Fig. 12. Deformation patterns for cylinder–ring combinations of (a) model I, inner and outer material C15E and (b) model J, inner and outer material C45E.

Fig. 13. Solid cylinder, initial height 60 mm, initial diameter 40 mm, (a) material C45E and (b) material C15E.

ring deforms in a manner very similar to that of a solid cylinder (see Fig. 13a). If this ratio is increased, the size of the mid-height cavity increases. If it is increased to 0.6, i.e. with a corresponding reduction in the wall thickness of the outer ring, then the deformation reveals a significant cavity at the cylinder/ring interface and a different external profile. For models C and D, there is evidence of a slight reversal in the curvature of the profile at the top and bottom of each specimen. For model D the curvature of the profile at the mid-height is very small. If the wall thickness is reduced further (model E) a double-barrel profile is clearly formed. This reveals that contact is maintained at the mid-height but two separate cavities are formed. Similar double-barrel profiles have been observed in earlier experimental work on hollow cylinders conducted by Hartley et al. (1981), as shown in Fig. 11. Similar features on the external profile for rings of a similar geometry are evident. The double-barrel profile seen in model E, corresponds with that shown in Fig. 14 (cylinder 30). In the case of this hollow cylinder, once the double-barrel profile developed it became unstable and further deformation resulted in the non-symmetric collapse of the ring. A solid cylinder at the core of the bi-metallic ring prevents such a collapse and allows the thin-walled ring to continue deforming in a more controlled manner.

Fig. 14 (cylinder 46) shows a very sharp point of inflexion at the inner surface mid-height. For the corresponding bi-metallic model (F), the transition at the mid-height is more gradual, due to the constraining effect of the inner ring.

There is some evidence (models C, D, E) of the upper and lower surfaces of the outer ring separating from the flat compression tools. This increases as the wall thickness of the ring reduces.

5.2. Inner material C45E, outer material C15E

If the materials are reversed so that the inner cylinder has a stronger material than the outer ring, as shown in Fig. 9, the general patterns of deformation are very similar, although there are a few subtle differences. There is slightly less conformity of the solid cylinder profile with the inner ring surface and therefore with a stronger cylinder the cavities are generally larger. In model D the outer profile at the mid-height is almost flat suggesting an earlier transition to a double-barrel profile than with the softer core.

Fig. 15 shows the influence of the ratio between the inner and outer diameters on the contact length for an initial height/outer diameter ratio of 1.5. While a weaker inner material shows a greater contact length (smaller cavity), both material combinations show a linear relation, with the contact length reducing as the diameter ratio increases. Fig. 16 shows that for an initial inner/outer diameter ratio of 0.6, an increase in initial height/outer diameter ratio

Fig. 14. Hollow cylinder deformation (from Hartley et al., 1981). The experimental geometry is that closest to the current FE models: (37) $H_o/D_o = 1.5$, $D_i/D_o = 0.375$ (model A), (35) $H_o/D_o = 1.5$, $D_i/D_o = 0.5$ (model B), (33) $H_o/D_o = 1.5$, $D_i/D_o = 0.624$ (model C), (31) $H_o/D_o = 1.5$, $D_i/D_o = 0.718$ (model D), (30) $H_o/D_o = 1.5$, $D_i/D_o = 0.812$ (model E), (46) $H_o/D_o = 1.0$, $D_i/D_o = 0.624$ (model F).
will result in a logarithmic increase in contact length (with a corresponding reduction in cavity formation). However, as the initial height is different for each point, the effect on the cavity size is not so obvious.

6. Conclusions

This study has shown that under certain conditions, bi-metallic rings may be upset while maintaining a good interfacial contact between the two components within a range of geometries. This establishes the possibility of producing bi-metallic components via this process either as a finished component or, more likely, as a pre-forming operation prior to further processing.

With an initial height/outer diameter ratio of 1.5, contact at the cylinder/ring interface is maintained over the most of the initially contacting surfaces. A small cavity is formed when the inner/outer ring diameter reaches 0.6. Above this value the cavity will become larger, and at 0.8 the wall thickness is sufficiently thin to allow a double-barrel outer profile to develop with two cavities. With an initial height/outer diameter ratio of 1.0 or less, the formation of interfacial cavities is much less and demonstrates the viability of producing bi-metallic components in this way.

For the examples here, the relative strengths of the two materials appeared to have only a small influence. The deformation is predominantly determined by the geometries of the two parts that constitute the bi-metallic ring.

References


