Finite element modelling of the evolution of surface pits in metal forming processes

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Abstract

The evolution of surface pits during forming of stainless steel has been investigated using the commercial ABAQUS finite element software. Both two-dimensional (2D) and three-dimensional (3D) models are presented and compared. No entrapment of lubricant has been considered in these current FEM simulations. The effect of surface hardening, friction and pit slope on the asperity flattening process is studied using the 2D model. The results show that surface hardening and friction have no significant effect on the flattening rate of the pit, while pits with smaller slope are eliminated more easily than steeper pits. It is also found that the contact area ratio predicted from the 3D model is much smaller than from the 2D model. Both 2D and 3D models predict that pit slope decreases with bulk deformation.

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1. Introduction

Surface roughness plays an important role in friction during cold metal forming processes such as rolling, drawing and upsetting. As Bowden and Tabor [1] suggested, contact junctions are formed between the tool and workpiece asperities in close contact. The area of these ‘real’ contacts is associated with the normal and tangential surface traction by McFarlane and Tabor [2]. This theory is consistent with the Coulomb–Amontons friction law that the friction force is proportional to the normal load. Problems arise with the simple model of asperity contacts at high normal pressures due to associated bulk plastic deformation and interaction of adjacent asperities. Greenwood and Rowe [3] found that the ratio of the true contact area to the apparent contact area (the ‘contact area ratio’ A) increases due to bulk deformation. Wanheim and Bay [4,5] investigated the interaction among adjacent asperities. Wilson and Sheu [6] proposed an upper-bound plane-strain model of surface asperity flattening in metal forming processes. It was shown that the hardness of an asperity is a function of the contact area ratio A and the non-dimensional strain rate (E) of the underlying material. Sutcliffe [7] developed a slip-line field analysis of the flattening process of surface asperities lying on a plastically deforming bulk material. The non-dimensional asperity flattening rate W was associated with the contact ratio A and the non-dimensional mean pressure p/2k. Both the upper-bound and slip-line field analyses predict that the ratio of contact area increases with bulk strain. This has been verified by rolling and plane-strain compression tests. These models have also been used in friction models in cold metal forming processes by Sutcliffe and Johnson [8] and Shu and Wilson [9] and recently by Lin et al. [10] and Marsault [11].

Makinouchi et al. [12,13] developed a finite element model to investigate the flattening of surface asperities under plane-strain compression taking into account elastic and plastic deformation in the underlying bulk material. Strain hardening of the material was also considered. The researchers investigated the sensitivity of the depth of the model on the results and found that a depth of twice the asperity spacing is sufficient to model the surface asperity deformation. The results confirmed that bulk plasticity enhances asperity crushing and that the contact area ratio increases with lateral tension under the same normal pressure. Korzekwa et al. [14] developed a robust finite element model to investigate asperity deformation where the underlying bulk material is subject to multi-axial straining. Results are presented in terms of the non-dimensional asperity hardness H, which is a function of contact ratio A and non-dimensional strain rate E. It was found that the form of the function is not affected by the lateral stress, the straining direction in the bulk material or the slope of the asperity. It was noted that the normal
velocity is quite uniform across the width of the valleys, implying that the shape of the valleys out of contact with the tool does not change significantly during deformation. The model has been applied to investigate the evolution of contact ratio in cold rolling processes by the authors [15–18]. Although a three-dimensional (3D) model was also described by Korzekwa et al. [14], the effect of the 3D nature on the surface asperity deformation was not detailed.

Concerns arise when modelling the evolution of surface pits during cold rolling of stainless steel. The strip is annealed, shot-blast and pickled to produce ‘white hot band’ which is then cold rolled. After the first cold rolling pass the pits have a characteristic diameter of about 70 μm and corresponding slope of about 15° [19,20]. As the pits are eliminated through the rolling schedule only small deep pits are left, so that the characteristic pit slope rises to 50° by the end of the schedule. There is a distribution of pits on the surface, all with very different shapes. Moreover, the surface pits are also of a 3D nature. The effect of these features on the elimination of pits is unknown. It is also noted that surface hardening is created by shot-blasting process prior to rolling. The role of this surface hardening is not clear. Finally, the effect of friction on asperity flattening has not been explored.

In this paper the finite element method (FEM) is used to simulate the flattening of surface pits on stainless steel in metal forming. The purposes are:

1. to verify the asperity flattening model used by Sutcliffe [15];
2. to investigate the effect of surface hardening on the asperity flattening rate;
3. to investigate the effect of friction on the asperity flattening rate;
4. to examine the effect of the 3D nature of the pits.

2. Finite element model

2.1. Geometry

Schematic diagrams of the 2D and 3D models are shown in Figs. 1 and 2, respectively. In both models, the tool surface is regarded as rigid and smooth. In the 2D model, one triangular pit is modelled using quadrilateral elements, due to periodicity. The initial contact area ratio \( A_0 \) is 0.5 and the initial pit spacing \( L_0 \) is taken as 300 μm (typical for a shot-blast surface). Note that the depth of the model is twice that of the pit spacing. The left side of the workpiece is regarded as the symmetric plane. The right side is moving at...
a uniform speed so that it remains vertical during the deformation process. A sliding velocity is imposed on the die surface for the case there is friction at the contact. In all cases, a thickness reduction of 15% was applied to the strip. An input file is entered directly and implemented in ABAQUS 5.8 [21].

In the 3D model, friction is not considered so that only a quarter of one pit needs to be modeled due to symmetry. The pit is conical with an initial slope of 30°, a spacing of 300 μm, a contact area ratio of 0.5 (giving a pit diameter equal to 240 μm) and a slope of 30°. The XZ and YZ planes are symmetric planes. The workpiece is under plane-strain conditions and it is extending in the OX direction with the front boundary remaining vertical due to periodicity. Hexahedral elements are used. An input file is produced by a pre-processor ABAQUS/CAE [22] and implemented in ABAQUS 6.2 [23].

2.2. Material property

The workpiece is an elastic-plastic von Mises material with strain hardening under plane-strain conditions. The Young’s modulus and Poisson’s ratio are 210 GPa and 0.3. A representative variation of plane-strain yield stress with strain for stainless steel is used, taking the curve for 316 stainless steel as supplied by the manufacturer. Corresponding values for the flow stress are 647 and 900 MPa at reductions of 0 and 15%, respectively.

The tool surface is in contact with the top surface of the workpiece. In the 2D model, the tool surface moves down from the top at a speed of \( V_t \) and slides in the horizontal direction at a speed of \( V_s \). Six cases are studied, as detailed in Fig. 4. Deformed mesh and Mises stress of the strip without surface hardening and friction using the 2D model.

### Table 1. Parameters used in FEM calculations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction coefficient</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>Surface hardening</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Reduction, ( r )</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Initial pit slope (°)</td>
<td>30</td>
<td>15</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Fig. 3. Hardness and equivalent strain on the surface of shot-blast white hot band.

Table 1. For Case 3 with surface hardening, an initial equivalent strain is applied to the surface, layer by layer, to satisfy the measured variation of hardness shown in Fig. 3 for the white hot band (i.e., strip which has been shot blasted prior to the cold rolling operations). Values for the hardness were estimated from micro-hardness measurements on sectioned

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**S, Mises**  
(Ave. Crit.: 75%)  

-8.40e+09  
+1.31e+09  
+1.22e+09  
+1.11e+09  
+1.04e+09  
+0.50e+08  
+6.80e+08  
+6.20e+08  
+5.30e+08  
+5.00e+08

Fig. 4. Deformed mesh and Mises stress of the strip without surface hardening and friction using the 2D model.
strips. For the 3D model, one case is presented to examine the effect of the 3D nature of the pit on its flattening rate.

2.3. Numerical procedure

The models are implemented by using a non-linear elastic-plastic finite element algorithm. The program is based on the variational principle with Lagrange multipliers. Two potential problems arise in the numerical implementation—the distortion of elements at the edge of the pits and the occurrence of intermittent contact between the tool and workpiece. For the low reductions used excessive element distortion was not found. The problem of intermittent contact was alleviated by using the soft contact behaviour available in ABAQUS. A typical case for the 2D model takes about 2 min to run on a Silicon Graphics workstation, while the 3D model takes about 5 min.

The deformed mesh and field output are viewed by ABAQUS/Post for the 2D model and ABAQUS/CAE for the 3D model. The surface data are analysed using a MATLAB
3. Results and discussion

3.1. Two-dimensional model

Case 1 is the reference case without surface hardening and friction. The deformed mesh and Mises stress are shown in Fig. 4. The perturbation of the deformation field associated with the pit extends to a depth equal to about one pit spacing. The most severe plastic deformation is underneath the contacts, while the region under the pit is still elastic. These results are similar to the slip-line field results of Sutcliffe [7] and the finite element results of Korzekwa et al. [14] and Makinouchi et al. [12,13].

The deformed mesh and Mises stress of Case 3, where there is surface hardening, are shown in Fig. 5. It is found that the high plastic strain region extends to the contact areas due to the high initial strain on the surface layers. However, the pit geometry is quite similar to Case 1.

When friction is included, as in Case 4, the deformation is no longer symmetric, as shown in Fig. 6. The pit moves forward in the sliding direction, although the pit size is similar to the reference case.

Fig. 7 compares the predicted evolution of maximum pit depth $\delta$ under these different conditions, with the model using Sutcliffe's [15] curve fit of Korzekwa's [14] finite element analysis. The effects of surface hardening (Case 3) and friction (Case 4) are insignificant. Sutcliffe's curve fit [15] slightly overestimates the flattening rate at small reductions but this is offset by an underestimate at higher reductions.

![Fig. 7. The effect of surface hardening and friction on the pit depth and comparison with the model by Sutcliffe [15].](image)

### Table 2

<table>
<thead>
<tr>
<th>Case</th>
<th>Contact ratio, $A$</th>
<th>Average slope ($^\circ$)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initially</td>
<td>0.5</td>
<td>30</td>
<td>Initial value</td>
</tr>
<tr>
<td>Case 1</td>
<td>0.80</td>
<td>24</td>
<td>Reference</td>
</tr>
<tr>
<td>Case 2</td>
<td>1.0</td>
<td>--</td>
<td>Small slope</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.79</td>
<td>21</td>
<td>Surface hardening</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.75</td>
<td>25</td>
<td>Friction</td>
</tr>
</tbody>
</table>

The pit with a smaller slope has almost disappeared, confirming previous theoretical results that the flattening rate increases with a reduction in pit slope [25,26]. The contact area ratio and average pit slope for these results are presented in Table 2. It is interesting to note that the average pit slope decreases slightly from its initial value of 30° to between 21° and 25°.

![Fig. 8. The deformed mesh and Mises stress at a reduction of 15% using the 3D model.](image)
3.2. Three-dimensional model

The deformed mesh and Mises stress of the 3D model, for which the model depth is equal to twice the pit spacing, is shown in Fig. 8. The perturbation in the deformation field associated with the pit is restricted to a depth of one pit spacing. The contact area ratio is 0.56 at a reduction of 15%. This is considerably less than the corresponding result for the 2D model of 0.80 (cf. Table 2). It is also found that the pit slope decreases from the initial value of 30° to about 20°. This change in slope has been neglected in previous models of friction and surface finish in metal forming. Due to the importance of pit slope, the variation of pit slope needs to be considered in future.

4. Conclusions

(1) A 2D finite element model is developed to investigate the effect of surface hardening, sliding friction and pit slope on the asperity flattening process under dry conditions. Theory predicts no significant effect of surface hardening or friction on the flattening rate, while pits with smaller slope are eliminated much more easily than steeper pits.

(2) The results are in line with the FEM results of Korzekwa et al. [14], as fitted by [15].

(3) The predictions of flattening rate and contact area ratio from a 3D model are significantly smaller than those of the 2D model.

(4) Both 2D and 3D models confirm that pit slope decreases slightly during deformation.

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References


