Influence of friction on roughening of the matt surface in aluminium pack rolling

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Received 1 June 2004; accepted 3 November 2004
Available online 9 December 2004

Abstract

A model has recently been presented to simulate inhomogeneous deformation of polycrystalline materials. This model was based on a finite element analysis using an isotropic plasticity model for the material with a distribution of strengths to simulate the crystallographic texture. By considering plane-strain compression of monolithic material, the displacements generated at the midplane successfully provided a prediction of the roughness at the interface of pack-rolled aluminium foil. In the current study, the predictions of the model are explored further. First, the influence of the friction coefficient $\mu$ at the interface between the sheets is assessed using a plane-strain compression model of two sheets. It is found that roughness does not depend greatly on $\mu$ when $\mu > 0.1$, being close to that predicted by the monolithic model. However, the roughness does increases significantly as $\mu$ falls below 0.1. Secondly, a plane-strain rolling model is used to clarify the effects of friction between the roll and the strip. It is found that neither the friction at the roll surface nor the roll diameter has a strong effect on the roughening of the internal matt surface. It is concluded that the model using plane-strain compression of monolithic material is appropriate to predict the roughness on the matt surface of pack-rolled materials.

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Keywords: Finite element analysis; Shear bands; Double rolling; Aluminium foil; Lubrication; Inhomogeneous deformation

1. Introduction

Pack rolling, wherein two stacked sheets of material are rolled at the same time, is widely used in the final pass during manufacture of thin aluminium foil. The rolled foil has a bright side where it is in contact with the ground rolls and a matt side at the interface between the two sheets of foil. The need to understand and control the evolution of this matt surface arises both from the user requirement for a controlled surface topography and because of the deleterious effect of excessive roughness on foil strength [1,2]. However, there is limited research on this topic.

A model has been recently presented [3–5] to predict the generation of roughness on the matt surface in pack rolling of aluminium foil. This model was based on the finite element method (FEM), with the material mechanical behaviour described using isotropic plasticity. The spread of crystallographic grain orientations was simulated by ascribing different material properties to each grain. This model requires less computational resources than the crystal-plasticity approach (e.g. [6]) but is still capable of simulating internal inhomogeneous deformation during bulk deformation processes. The prediction showed good quantitative agreement with experiments as well as with predictions using crystal-plasticity [5]. It was found that the formation of shear bands causes peaks and valleys in the roughness topography running in the transverse direction on the matt surface. These predicted topographical features agree with experimental observations [1,2,7–9].

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doi:10.1016/j.ijmachtools.2004.11.009
However, two significant simplifying assumptions were made in the previous studies [3–5]. First, the material was treated as a monolithic material so that the profile at the midplane was taken as the profile of the matt surface. In practice, conditions at this interface are affected by lubricant applied there, which is required to allow subsequent separation between the two sheets, even though this lubricant is said to cause a deterioration in the matt surface finish [1]. Hence, it is industrially important to show how the friction at this internal interface affects the roughness.

In this study, two aspects are explored. Firstly, a plane-strain compression (PSC) model of two sheets is used to assess the influence of the friction coefficient between the sheets. Secondly, the deformation in rolling was approximated in previous studies by plane-strain compression. It has been found experimentally that roughening on the matt surface is insensitive to changes in both the friction on the roll surface and the roll diameter [8]. In the current work, a rolling model is developed to investigate the relationship between the friction on roll surface and the roughness on the matt surface, using the isotropic finite element (FE) method.

2. Model description

2.1. Material model

The model is based on the finite element method using isotropic plasticity, closely following the methodology of [3–5]. The spread of crystallographic grain orientations is simulated by ascribing different material properties to each grain, with the spatial distribution chosen at random. The material is assumed to be commercial-purity aluminium. A triangular probability function, where the minimum, mid-point and maximum strengths are 55, 85 and 140 MPa, respectively, is assumed for the initial yield stresses. A linear work hardening law is assumed. Making the assumption that the yield stress \( Y \) scales with the Taylor factor \( m \), while the hardening modulus \( H \) scales as the Taylor factor squared, then for a given value of yield stress \( Y \) the corresponding hardening modulus \( H \) is given by \( H = H_{\text{mid}} (Y/Y_{\text{mid}})^2 \), where the subscript\( \text{mid} \) denotes the mid-value. Therefore, the distribution of flow stress broadens with an increase in strain applied. The material is treated as elastic–plastic, with an elastic modulus \( E (= 70 \text{ GPa}) \), Poisson’s ratio \( \nu (= 0.3) \) and a mid-point hardening modulus \( H_{\text{mid}} (= 300 \text{ MPa}) \). The incorporation of the experimental material properties to the model was discussed in [4].

2.2. Plane-strain compression model of two sheets

The model used is shown schematically in Fig. 1. The finite element mesh has 12 four-noded quadrilateral elements through the thickness \( t = 2h \) and 120 elements along the length \( L \). Uniform square grains of two sizes are considered. For the fine grains, one element represents one crystallographic grain in the mesh, so that there are 12 grains through the thickness \( t \). For the coarse grains, one grain is mapped to \( 2 \times 2 \) elements, giving six grains through the thickness. In other words, the side length of the square grain \( d \) equals \( \Delta \) for fine grains and \( 2 \Delta \) for coarse grains, where \( \Delta \) is the initial element length. For each grain size, an identical spatial set of material properties is used. The thickness is reduced by 40% in the plane-strain compression simulation (PSC), and the boundary conditions at the top and the bottom external surfaces simulate frictionless conditions there. The left end is constrained to remain vertical. The deformation is analysed by a commercial FEM package ABAQUS version 6.35 [10]. Although a two-dimensional (2D) PSC model is used in this study, it was shown that the corresponding three-dimensional analysis which allows out-of-plane straining of individual grains shows similar trends, though predicting lower roughness amplitudes [5].

The Coulomb friction coefficient \( \mu \) between the two sheets is varied between 0 and 0.3. The ‘master and slave’ algorithm in ABAQUS is used for the contact analysis. In normal use, slave nodes are constrained not to penetrate into the master surface; however, the nodes of the master surface can, in principle, penetrate into the slave surface. In the current work, both the upper and lower interfaces are prescribed as ‘master’ as well as ‘slave’ surfaces, so that both surfaces are treated equally within each increment. For comparison, the analysis is also performed with the monolithic model (i.e. without an internal interface).

2.3. Rolling model to investigate the effects of rolling conditions

To investigate the validity of using the plane-strain compression simulation to model roughness generation during rolling, the rolling model shown schematically in Fig. 2 is used. As the spatial distribution of material properties is not symmetrical with respect to the midplane, a full rather than a half model is adopted. The material is assumed to be monolithic in these simulations. The FE mesh has 12 four-noded quadrilateral square elements through the thickness \( t = 2h \) and 240 elements along the length \( L \). One element represents one crystallographic grain in the mesh, so that there are 12 grains through the thickness \( t \). An identical spatial set of material properties is used for the different rolling conditions. Two roll sizes are compared.
with the ratio of the roll diameter $D$ to the total sheet thickness $t = 2h$ being 100 or 10. The Coulomb friction coefficient between the roll surfaces and the external surfaces of the strip $\mu_r$ is varied from 0.1 to 1.0. The thickness is reduced by 40% in one rolling pass. The leading end of the material is initially truncated so that there are some surface nodes in contact with the rolls at the start of the deformation, ensuring a stable start to the rolling simulation without slippage. The profile of the mid-plane of the material rolled under steady state conditions is taken as the profile of the matt surface. As the model is asymmetric, the exiting rolled material typically shows a slight curvature. This is eliminated by fitting a 3rd order polynomial curve to the deformed mid-plane profile.

2.4. Rolling model to investigate the effects of grain size and shape

To investigate the influence of the microstructure, a rolling model described above is used. Numerical conditions are chosen to compare the results with those of PSC [3]. The number of grains through the thickness $t$ is varied, with 6, 12 and 18 grains being considered. Both cubic and rectangular grains are used. The length of rectangular grains is four times their thickness ($4 \times 1$) and they are arranged in an overlapping ‘brick wall’ pattern. The ratio of the roll diameter $D$ to the total thickness $t$ is 100. The friction coefficient between the rolls and strip surfaces $\mu_r$ is 0.1. A higher thickness reduction of 50% is applied to compare results with those of PSC [3].

3. Results and discussion

3.1. Plane-strain model with two sheets: influence of friction

Fig. 3 shows part of the deformed mesh for the plane-strain compression simulation with two sheets and the coarse-grained material. Shear bands are formed, running along inclined directions through both sheets. The previous studies [3,5] revealed that shear bands initiate from a few weak grains and propagate at $45^\circ$ to the rolling direction. They are most marked in the case without friction Fig. 3(a). Relative displacement between the two sheets at their interface can clearly be seen in the simulations Fig. 3(a)–(c) for the two sheet model, with the greatest displacement occurring for the case without friction Fig. 3(a), decreasing with an increase in the friction coefficient. For the case of $\mu = 0.3$, Fig. 3(d), the relative displacement is negligible, so that the deformation is close to that of the monolithic model, Fig. 3(e). As an identical set of material properties was used in these simulations, peaks or valleys are generated at similar longitudinal positions irrespective of friction.

The $R_a$ roughness amplitude on the matt surface, normalised by the grain size $d$, is shown as a function of the friction coefficient $\mu$ in Fig. 4. The upper and the lower
matt surfaces have virtually the same amplitude, as their profiles are almost identical. The roughness increases with a decrease in the friction coefficient $\mu$, for $\mu < 0.1$. With $\mu > 0.1$, the roughness is not sensitive to the friction coefficient. The roughness predicted with $\mu > 0.03$, is slightly smaller than the value predicted by the monolithic model. Fine-grained material generates higher roughness $R_a/d$, as reported in [3,5]. If normalised by the initial thickness $R_a/t$, the fine-grained material generates lower roughness. Therefore, fine-grained material is favourable for the production of a smooth matt surface. This is because, in fine-grained material, the number of shear bands is larger and the resultant deformation is more homogeneous.

The influence of friction between the two sheets can be explained as follows. For very small friction coefficients, there appears to be a tendency for an instability to form, with alternating regions along the length of each strip of small and large elongations, mirrored on the opposing surface, see Fig. 3(a). This results in a relatively high wavelength, large amplitude, interface between the strips. The horizontal slip required by this deformation mode is prevented where the friction between the two strip surfaces is sufficiently high.

Pioneering experimental work on the influence of friction on the roughening of matt surface was reported in [1]. It was shown that lubricant between the sheets increases the roughness. The effect is further studied in [9], where the roughnesses of foils rolled with two lubricants having kinematic viscosities of 2.4cSt or 9.5cSt, respectively, and of foil rolled without lubricant, were compared. It was concluded that thicker lubricant results in higher roughness on the matt surface. Material rolled without lubricant showed the smoothest matt surface. These experimental results agree well with the current numerical predictions, associating lower values of $\mu$ with the thicker lubricants. If application of lubricant is necessary for the separation of two sheets after pack rolling, the current results suggest that lubricant giving higher friction (e.g. associated with the thin films expected with low viscosity lubricants) is preferable. When $\mu$ is greater than 0.03, modelling the two sheets separately is not necessary as the monolithic model gives a reasonable approximation.

### 3.2. Rolling model: influence of friction at the roll surface and roll diameter

In this section, we compare a rolling model for monolithic strip with plane-strain compression simulations, investigating the effect of friction at the roll/strip interface and the effect of the roll diameter. Typical snapshots of the deformed mesh at the roll bite during deformation are shown in Fig. 5 (a)–(c). For comparison, the mesh after PSC without friction is shown in Fig. 5(d). Elements in the strip near the roll
surfaces are sheared by friction from the rolls. Larger rolls or higher friction coefficients results in severe shear deformation, known as ‘redundant shear deformation’ [11]. Shear bands through the thickness are also observed in the rolled material, most clearly seen in Fig. 5(a). The mesh distortion around the midplane is similar for the four cases shown in Fig. 5. The profiles on the midplane after rolling or PSC are compared in Fig. 6. The curvature due to the asymmetrical rolling conditions has been removed from these profiles. These profiles were taken from the region which was rolled under steady state and where an identical spatial distribution of material properties was prescribed. If the friction coefficient $\mu_r$ between the roll and strip is low, Fig. 6(a), the profile is almost identical to that of the PSC simulation, Fig. 6(d). A higher friction coefficient, Fig. 6(b), generates a similar profile to Fig. 6(a), although with more small peaks or valleys. The longitudinal position of peaks or valleys occasionally shifts slightly. Small rolls Fig. 6(c) produce a similar profile as the larger rolls Fig. 6(b), but the amplitude is slightly smaller.

The effect of the relative thicknesses of the two strips on the roughness generated at their internal interface is found by calculating the $R_\alpha$ roughness at successive planes through the thickness, i.e. for planes closer to the roll surfaces, as opposed to the mid-plane results presented above. The variation of this roughness with position from the midplane, normalised by the total sheet thickness, is shown in Fig. 7. With larger rolls ($D/t = 100$, cases (a) and (b)), the maximum roughness can be found around the midplane, decreasing toward the roll surfaces. The profile with a low friction coefficient $\mu_r$, case (a), is close to that of the frictionless PSC, case (d).

The friction coefficient $\mu_r$ does not have a strong effect on the roughness around the midplane. However, the roughness near the external surfaces increases with $\mu_r$. This shows that the redundant shear deformation present in the rolling deformation does not have a strong effect on the roughness generated at the midplane, but does increase the roughness near the external surface. This is due to the higher equivalent strain in these regions. The variation of roughness with position for the material rolled with small rolls, case (c), shows two peaks approximately equidistant between the midplane and the roll surfaces. This is due to the geometry of the roll bite, in particular the shorter contact length. There are two types of shear deformation occurring during rolling. The first one is the frictional shear deformation discussed above. The other is the internal shear deformation that occurs due to the change in velocity of metal flow. The first type is generally predominant in foil
rolling, while the latter is dominant when the rolls are smaller or the material is thicker, as in case (c) [12].

In Fig. 8, the roughness normalised by the grain size \( R_{a/d} \) is shown as a function of the friction coefficient on the roll surface \( \mu_r \). For \( \mu_r = 0.1 \), rolling with small rolls \( (D/t = 10) \) was not possible in the simulation, due to the lack of a frictional force to drag the material through the bite. If the friction coefficient is low, the roughness predicted by the rolling model is very close to that of the PSC simulation. The predicted roughness does not vary significantly with the friction coefficient \( \mu_r \) at the roll surface.

The above results show that the roll diameter and the friction coefficient \( \mu_r \) on the roll surface have little influence on the roughness on the matt surface; experimental studies have shown similar insensitivity of roughness to roll diameter and friction coefficient [8]. This is due to the fact that the midplane is not affected by the surface shear deformation and so is subjected to deformation close to PSC conditions. It can be concluded that the roughness on the matt surface of pack-rolled material does not depend significantly on the rolling conditions. Therefore, the PSC model is appropriate to predict the roughness on the matt surface of pack-rolled materials.

### 3.3. Rolling model: influence of grain size and shape in rolling

Rolling simulations were undertaken to investigate the effect of grain size and shape on roughness generation, applying a thickness reduction of 50% with large rolls \( (D/t = 100) \) and low friction \( (\mu_r = 0.1) \). The predicted roughness for the various simulations are shown as a function of the grain size and quantitatively compared with the previous PSC results [3] in Fig. 9. The roughness normalised by the grain size \( R_{a/d} \) increases with the number of grains through the thickness. The roughness decreases as the grain size decreases as can most clearly be seen in Fig. 9(b), where the roughness normalised by the initial thickness is plotted as a function of the normalised grain size. Materials with finer grains are desirable to obtain a smoother matt surface. The rectangular grains follow a similar trend, although with a slightly lower roughness than the cubic grains. The predicted influences of the grain size and shape in rolling are very similar to those in PSC, confirming that the PSC model is a reasonable approximation of pack rolling to predict the roughness on the matt surface.

### 4. Conclusions

This paper considers the generation of roughness on the internal surface during pack rolling using an isotropic FE model. A comparison between plane-strain compression and rolling simulations is undertaken. The influence of two forms of friction, (i) friction between the sheets and (ii) friction between the roll surface and the sheets is investigated. The following conclusions may be drawn.

1. The matt surface roughness amplitude increases significantly as the friction coefficient between the sheets falls below 0.1.
2. If the friction coefficient between the two sheets is greater than 0.1, the surface roughness does not depend significantly on the friction coefficient. The predicted roughness is close to that of the monolithic model.
3. Neither the roll diameter nor the friction coefficient on the rolls have a strong influence on the roughness at the matt surface. Plane-strain compression is a reasonable approximation of 2D rolling for the prediction of the roughness on the matt surface.
4. The influences of grain size and grain shape in rolling are similar to those in plane-strain compression. The roughness normalised by the initial thickness \( R_{a/t} \)
decreases with a decrease in the grain size. Fine-grained material is desirable for a smooth matt surface.

Acknowledgements

The authors wish to thank Dr Keith Waterson at Kingston Research and Development Centre, Alcan International Limited for his advice. Financial support from Alcan International Limited is gratefully acknowledged.

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