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Mechanisms of surface deformation during cold rolling of aluminium

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The main surface features found during cold rolling of initially twin-rolled cast aluminium are grooves, gorges, shingles, cross hatches and rolling ridges. Grooves–shingles are formed at the exit side of the neutral plane during casting and these are deformed into gorges in the first pass and the shingle is smeared over the cavity. A large number of shingles are formed in the second pass from steps in the surface resulting in interfaces within the surface region. Due to the following extension of the sheet and the shift in rolling direction these interfaces will be extended and new interfaces formed by additional smearing out of steps, resulting in a laminated structure in the surface. Cross hatches are formed in these laminated areas. Later passes cause the cross hatches to grow and new ones to be formed.

1. Introduction

The surface structure of aluminium sheets cold rolled from twin-roll cast sheet, is important for a product's properties, such as appearance, formability and corrosion resistance. This structure is determined both by the initial surface structure of the twin-roll caster rolls and by deformation of the surface in subsequent passes during cold rolling. However, previous work concerning deformation of surface structure has focused on flattening of peaks and rolling ridges [1–4] and not on the wide range of surface features found during rolling. Phenomena like grooves [5, 6] and shingles [5] are only occasionally reported in connection with hot rolling of aluminium. The dependency of the initial topography in combination with the different passes do not seem to be treated in the literature. Consequently, some important aspects needed to understand the mechanisms operating in the roll gap, are missing. Therefore, the present work has concentrated on the governing mechanisms creating and deforming the surface features of twin-roll cast aluminium sheets.

In order to optimize and control the final structure of the surface it is important to systemize the observations to determine the main mechanisms. The surface structure of each pass of the cold rolling sequence of initially twin-roll cast sheets has therefore been characterized in a previous work [7], which describes how the characteristic surface features change during subsequent passes. The present work focuses on description and interpretation of how selected surface features evolve. Following preliminary studies the cases that are focused upon are grooves, gorges, shingles, cross hatches and rolling ridges.

2. Experimental procedure

Two coils of an aluminium 3003 alloy (1 wt% Mn) have been twin-roll cast. One coil was selected from a relatively early and one from a late stage in the lifetime of the casting rolls to achieve large but realistic variations in the initial surface structure spanning from fine to rough. The coils were processed through a four-high industrial cold rolling mill. They were cooled between passes and the direction of rolling was reversed in each pass. The upper side of the cast sheet was kept as the upper side through all the cold rolling passes. The reduction from as-cast (6 –7 mm) to final thickness (0.69 mm) was done in six passes (Table I) without interannealing. Specimens were taken from each pass from alternating ends of the coils near the middle of the coil width.

The surfaces were characterized using optical microscopy (Leica MEF), Scanning Electron Microscopy (SEM, Philips 30X) and Laser Scanning Microscopy (LSM) (Zeiss LSM). The LSM gave three-dimensional images of the surface topography.

In this work experiments with model material (wax) were performed to test hypothesis of the deformation sequence and mechanisms operating in the roll gap during cold rolling. The experiments with model material were performed on a laboratory rolling mill where the rolls were made of transparent polymethylmethacrylate (PMMA). The speed of the rolling mill could be changed continuously from 0 to 0.63 $m\,s^{-1}$, the roll gap could be set up to 100 mm and the roll diameter was 600 mm.

3. Results and discussion

Previous work [7] has shown how grooves–shingles in the surface of the as-cast pass are deformed during the cold rolling process. The grooves are formed into gorges and the shingles are partly smeared over the gorges in the first pass. The steps and peaks resulting from this are smeared out as shingles in the second pass. These shingles do not completely adhere to the

TABLE I Reduction of the aluminium sheet through each cold rolling pass

Pass No.	0	1	2	3	4	5	6
Thickness, mm	6–7	4.6	3.0	2.0	1.35	0.9	0.67
Thickness reduction, %		30	35	33	32	33	25
Extension, %		133	153	150	148	150	134

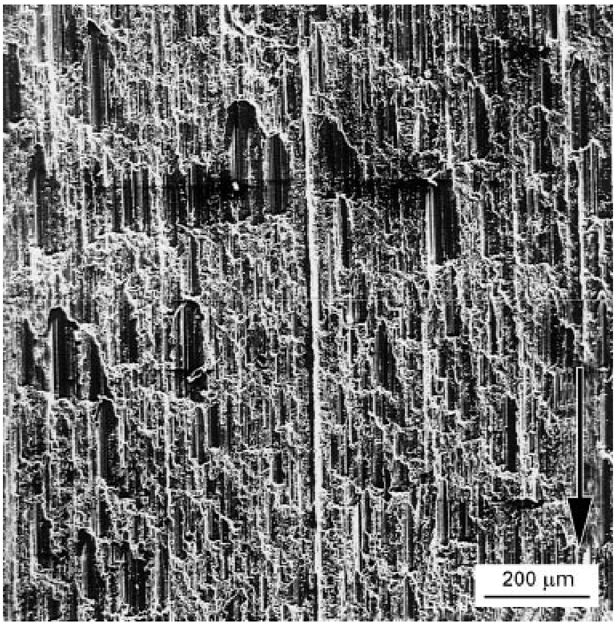


Figure 1 SEM micrograph showing grooves with following shingles (the arrow indicates the casting direction).

underlying bulk material and consequently deform heterogeneously on further rolling. Cross hatches may develop on the surface of the shingles. The cross hatches increase in size and spacing with successive rolling and new ones are formed. In the present work, each phenomenon is studied in further detail, and changes from pass to pass are seen in relation to one another.

3.1. Formation of grooves–shingles during twin-roll casting

Grooves are an important characteristic of the as-cast sheet surface in twin-roll casting (Fig. 1) in the same sense as the pickup grooves found in hot rolling. However, the origin of these two types of grooves is quite different. In *twin-roll casting* the grooves can be created by peaks or blades on the roll surface [8] and thereby be followed by a shingle. This mechanism is discussed in the following.

The formation of a groove has been studied by the use of idealized wax experiments in a roll gap with knobs protruding out of the roll surface. Deformation in the roll gap is illustrated in Fig. 2. These observations are combined with calculations of the relative motion between the roll/knob and the sheet using a simple slab analysis:

1. In the entrance of the roll gap, the rolls move faster than the sheet. The knob touches the surface of

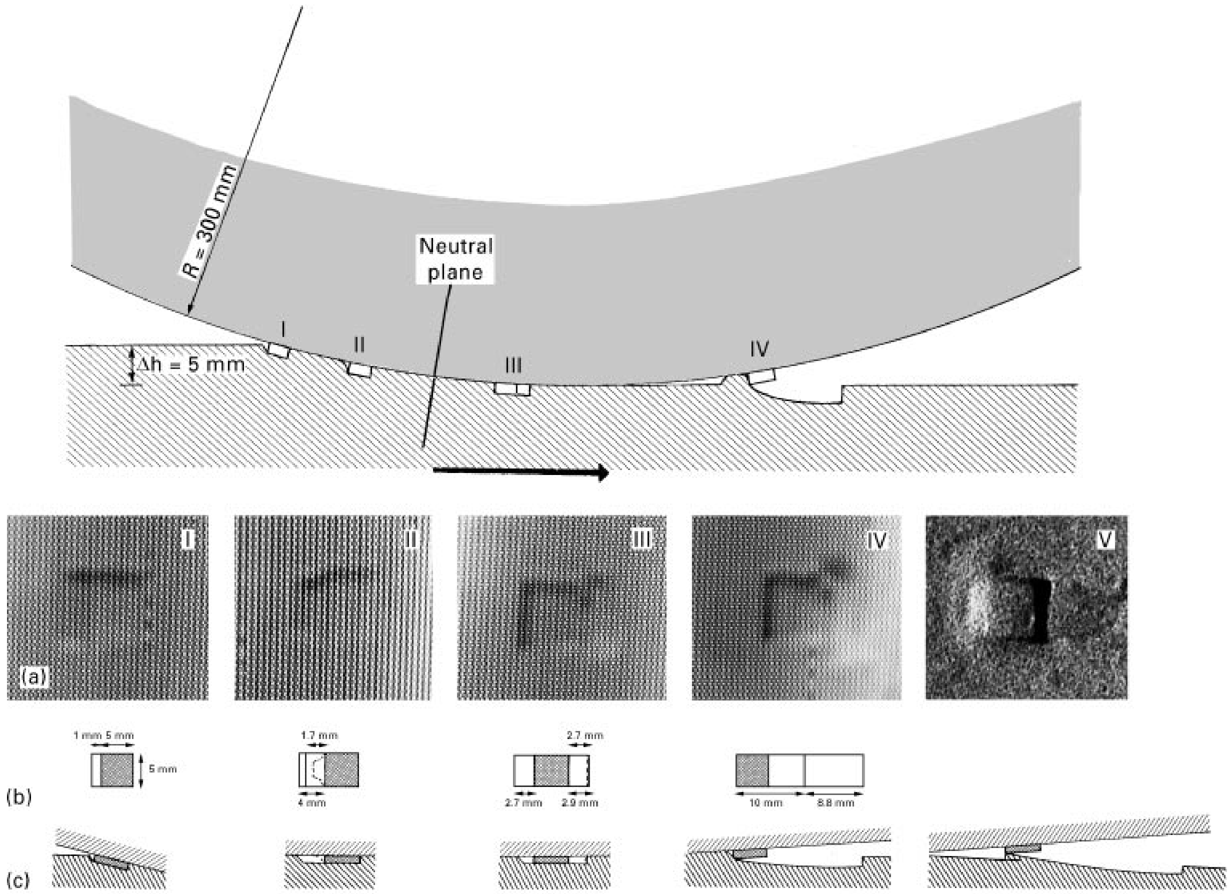


Figure 2 Illustration of how a groove is formed in the experiment (20 mm slab) at five different stages through the roll gap. Tne stages are taken at approximately: I, 0 mm; II, 14 mm; III, 48 mm; IV, 53 mm into the roll gap; and V, after the roll gap at 55 mm. (a) Images from the video of the cast experiment, (b) surface view of the calculated groove (full line) and the observed groove in Fig. 2a (broken line), and (c) a longitudinal section of the same grooves.

the sheet before the sheet enters the roll gap, and digs out a gently sloping groove in the surface of the sheet.

2. As the sheet enters the roll gap, the knob is moved forwards relative to the sheet. Material is thus compressed on the front side of the knob and the groove grows on the rear side. As a result of the high pressure in the roll gap, the bottom is pressed towards the surface of the roll and the upper part of the wall moves into the groove, as these are free surfaces and do not experience a plastic constraint. Transverse sections of a rectangular aluminium groove are shown in Fig. 3, before and after rolling. It is confirmed that the groove wall has moved inward and the bottom upward, thereby almost filling the groove. The corner region is constrained by the surrounding material and therefore moves very little inwards compared with the large flow of the upper part of the wall.

It is seen in Fig. 2a, at Stage II that the wax groove narrows towards the entrance of the roll gap. This is because closing of the groove is constrained by the knob at the front end. As the knob approaches the neutral plane, the groove is closed. This shows that the grooves dug at the entrance side of the neutral plane are closed except for a small (or no) groove at the rear side of the knob as it passes the neutral plane.

3. When the knob passes the neutral zone of the roll gap, the sheet moves faster than the rolls. Hence, the knob moves backward relative to the sheet and a groove will appear on the front side of the knob (Fig. 2, Stage III). This groove will not be closed like the groove at the entrance side of the neutral plane because the reduction and pressure is low at this stage. The length of the flat part of the groove is therefore given by the length of the groove dug at the exit side of the roll gap.

4. The sheet leaves the roll gap with the knob still in contact with the surface of the sheet. A gentle slope is consequently dug by the knob at the rear end of the groove (Fig. 2, Stage IV). The material from the groove will be heaped up on the rear side of the knob, as indicated in the sketch in Fig. 2c, Stage IV.

5. As the knob and the sheet moves further away from the exit of the roll gap, the material accumulated on the rear side of the knob will be smeared backward onto the sheet (Fig. 2, Stage V). This creates a shingle behind the groove, where the length of the shingle increases with, for instance, the height of the knob and the reduction.

The grooves observed in the wax experiment generally have the same appearance as the ones on the cast aluminium sheets. They are steep sided and are followed by shingles (Fig. 1). This indicates that the groove and the shingle are formed by a knob with steep sides both parallel and normal to the rolling direction, as discussed above.

In the entrance to the casting rolls the aluminium solidifies against the surface of the rolls, and sticks to the rolls. The sticking will probably be retained well into the roll gap so the deformation due to the difference in speed will be transferred some distance into the aluminium. Large grooves will thereby not be dug on the rear side of knobs as described for the wax experiment. However, simple slip-line fields show that the deformation field on the exit side of the twin-roll caster is similar to conventional rolling, which means that there is some sliding. The formation of grooves is thereby qualitatively similar for the twin-roll cast sheet and the wax experiment. Therefore, the

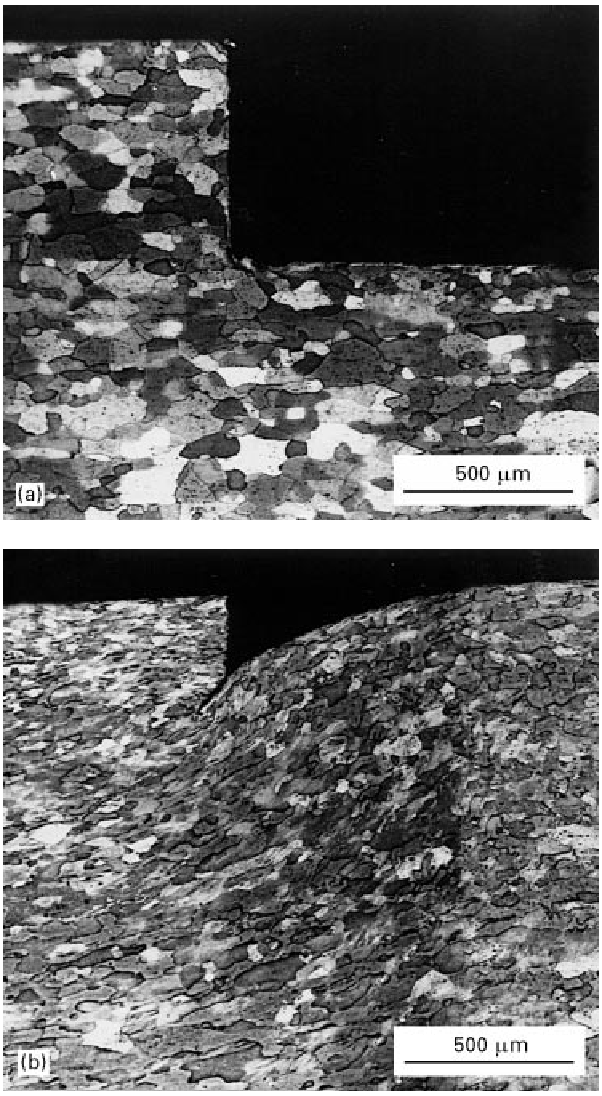


Figure 3 Optical micrograph of a rectangular groove in transverse section before (a) and after (b) rolling.

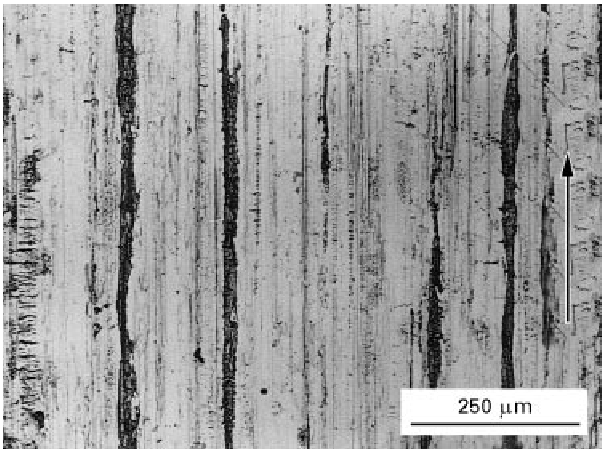
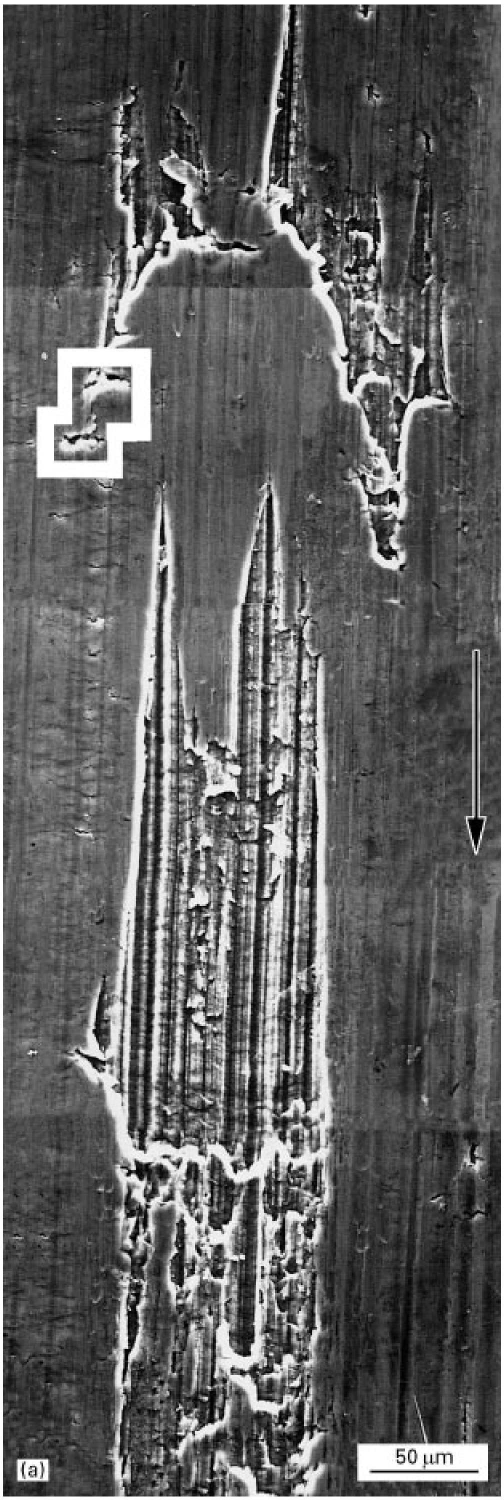


Figure 4 SEM micrograph of gorges from the first cold rolling pass of the initial groove in twin-roll cast material (the arrow indicates the rolling direction).



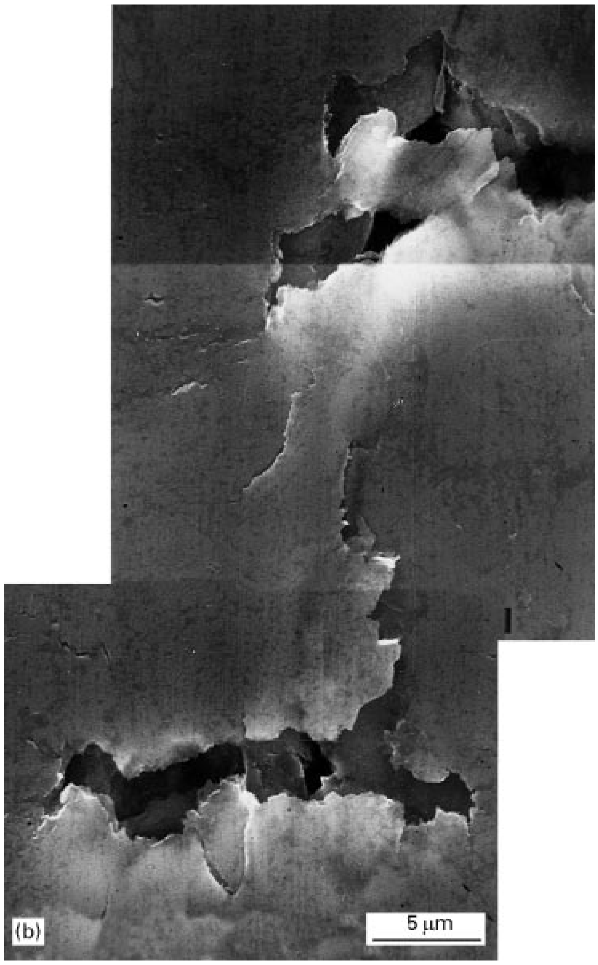


Figure 5 (a) SEM micrograph of a typical gorge in the first pass, and (b) detail showing how the material is deformed in the junction between the shingle and the side of the groove (indicated by the frame in Fig. 5a).

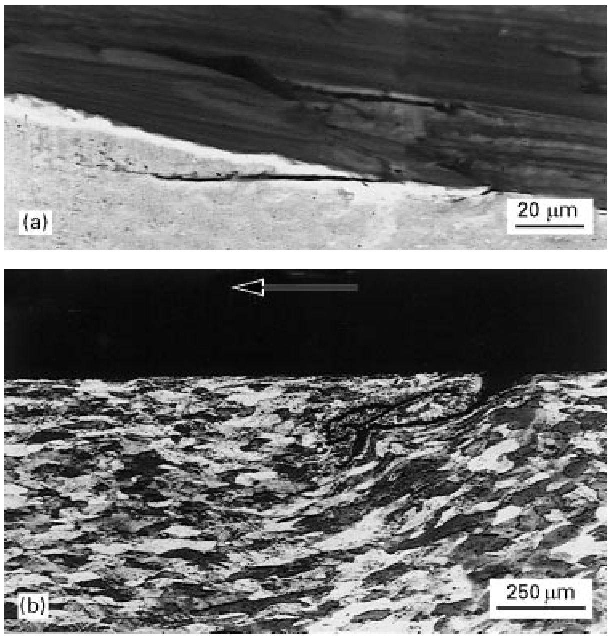


Figure 6 (a) SEM micrograph of a longitudinal section of a flattened shingle tip, and (b) optical micrograph of the idealized case.

groove–shingle are proposed to be created in the same way. Thus the size of the groove is determined by the final sliding and the topography of the rolls.

3.2. Deformation of grooves into gorges in the first cold rolling pass

The rolling direction shifts in the first cold rolling pass, which means that the shingle enters the roll gap before the groove. This causes the shingles, which are above the general level of the surface at this stage, to be flattened and partly smeared over the groove while the grooves are deformed into long narrow gorges (Fig. 4). The gorge shown in Fig. 5 is typical of the first pass. The shingle will experience a higher pressure than the surroundings and the tip will thereby be pressed into the surface and the boundary of the shingle tip will form a crack (Fig. 6a). This is valid, as seen

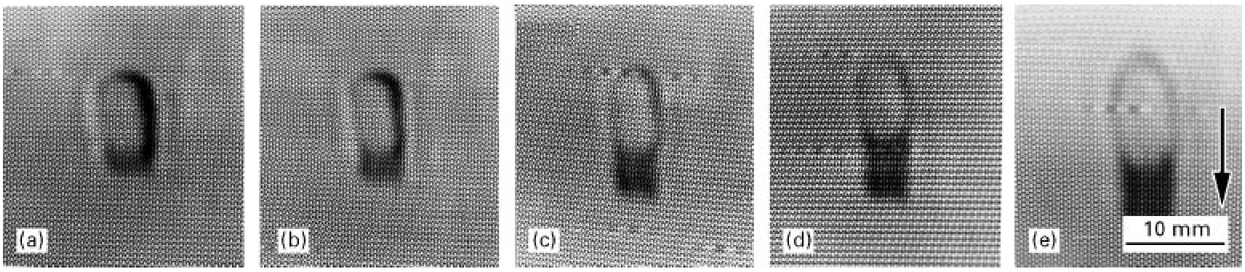


Figure 7 Images from the video, the first rolling pass of the 80 mm slab. The images are taken at approximately: (a) 0 mm, (b) 4 mm, (c) 12 mm, (d) 31 mm into the roll gap; and (e) outside the roll gap, where the roll gap is 58 mm long.

for a shingle and confirmed by the rolling of an idealized shingle tip (Fig. 6b), which shows the same deformation.

If the strain induced on the shingle is larger than the bulk sheet is able to absorb (Fig. 5), the material in the shingle must be smeared over the groove because the material can flow freely only in this direction. The shoulders of the shingle will then meet the top edges of the gorge walls. At the same time the gorge walls are elongated and form cracked overhangs [7]. The gorge in Fig. 5a shows a typical junction between a gorge wall and a smeared shingle, where details are shown in Fig. 5b. It can be seen that the material on either side of the junction has experienced different speeds. This is caused by the shingle moving more freely than the edge of the gorge. The material has therefore been sheared along the junction and fragments within the junction have been torn and rotated.

The deformation of the groove itself is simulated by rolling of wax with grooves (Fig. 7). It is observed that the depth of the grooves especially in the middle of the groove is reduced. This is similar to what happened on the entrance side of the neutral plane in the zero pass. In addition to the closing of the groove both from the sides and the bottom, the groove is stretched in the roll gap. As the first groove slope enters the roll gap, the upper part of the slope will be stretched forward relative to the lower part due to the difference in speed between the sheet and the rolls. However, the rear groove slope will meet the material on its entrance side and is withheld relative to the rolls. Most of the stretching of the groove at the entrance side of the neutral zone is therefore absorbed by the first part of the groove. As the groove passes the neutral plane, the sheet will move faster than the rolls, and the rolls will withhold the rear groove slope. This slope will now be stretched, but to a smaller degree because the reduction is lower at the exit side of the neutral zone.

The general impression of the changes of the grooves from the zero to the first pass in the wax experiments and in the twin-roll cast aluminium sheets, is similar. The grooves on the aluminium sheets are reduced in depth and width as well as being lengthened [7].

It is clear that the front part of the groove slopes more gently after reduction in the case of both aluminium and simulated wax. The sharp side is smoothed as the upper part follows the rolls and the lower parts follow the underlying material.

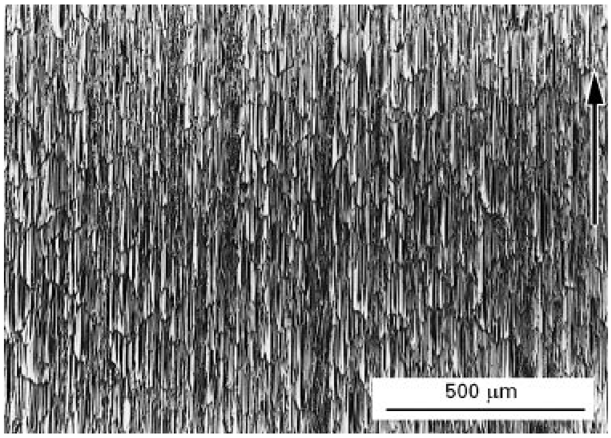


Figure 8 Optical micrograph of large shingles that totally cover the surface of the sheet after the second pass.

3.3. Formation of shingles

A shingle can normally be described as a tongue on top of the surface where the tip of the tongue points opposite to the rolling direction. Shingles are assumed to be assisted by local adhesion or sticking followed by deformation into unconstrained regions and finally rupture of the contact as the sheet moves away from the rolls [5, 9]. The present work gives a description of the shingles, combined with an analysis of those features that result in shingles.

The main group of shingles is large, totally covers the surface and is generally found in the second pass (Fig. 8). These shingles are thick and lie on top of the surface (Fig. 9a). There is often an interface between the shingle tip and the surface, as shown by the longitudinal section (Fig. 9b). The shingle tip can protrude out of the surface (Fig. 9c, d), and the edges or shoulders of some of the shingles can be cracked (Fig. 9e).

These large, thick shingles must originate from features in the previous pass that produce locally high friction and that have a neighbouring unconstrained region. Large steps or peaks will satisfy these requirements (Fig. 10). The shear caused by the difference in velocity will attack the peak–step and smear these forward and backward. At the entrance side of the neutral plane, the top edge of a step (Fig. 10a) will be drawn forward, while the height reduction of the step will cause a backward material flow so that the steep edge of the step will be maintained. At the exit side of the neutral plane, the step will be smeared backward and produce a shingle on the sheet.

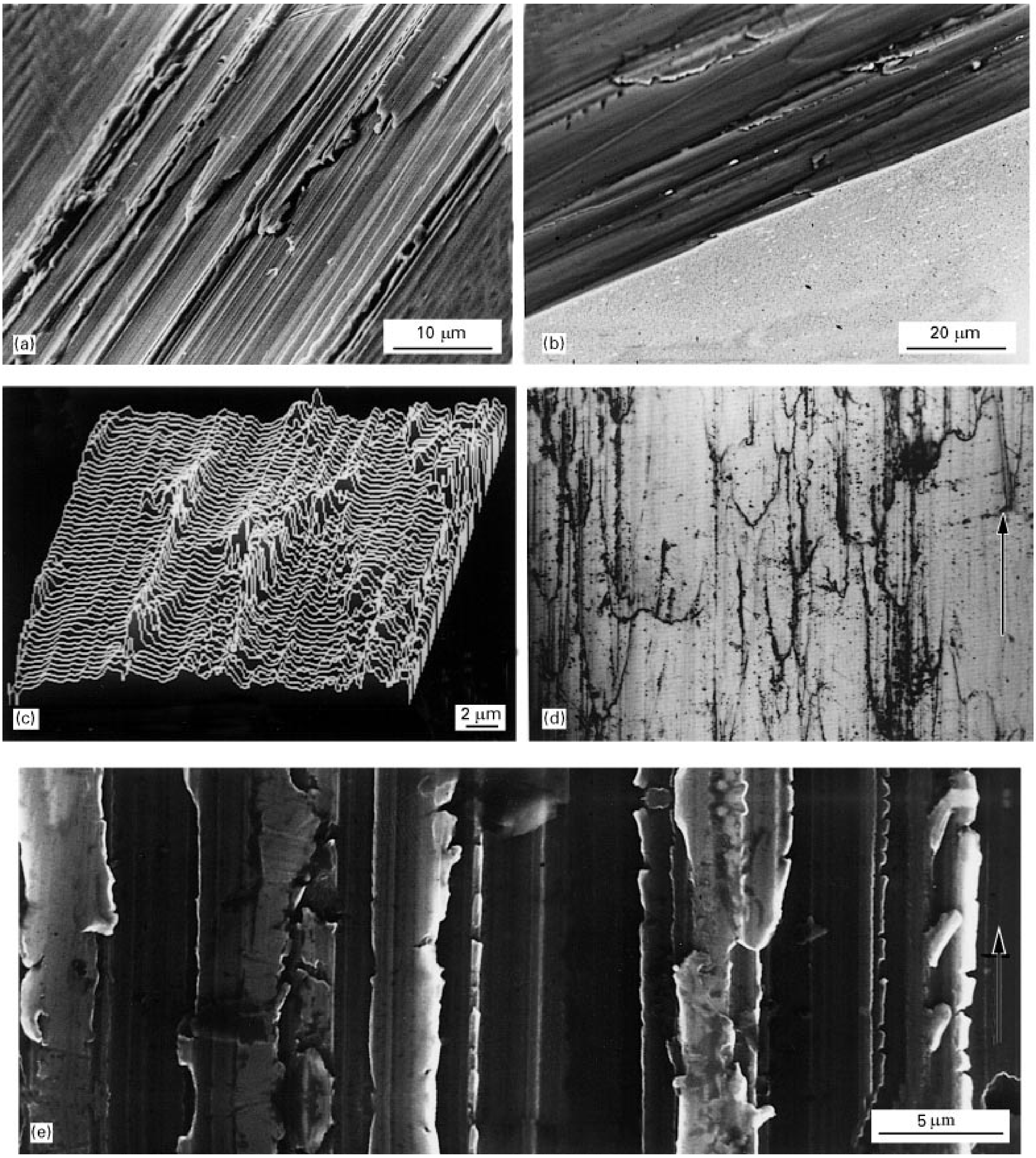


Figure 9 SEM micrograph of (a) thick shingles lying on the surface (b) a longitudinal section of a shingle. (c, d) Three-dimensional LSM image and corresponding EDF image showing how the shingle tip protrudes out of the surface. (e) SEM micrograph of cracks on the shoulders of the shingles.

For an oppositely directed step (Fig. 10b), the edge will be smeared forward and the material in front of the step will be pushed towards the rolls so that a crack pointing backwards is formed. This is similar to what is shown in Fig. 6.

A peak (Fig. 10c) will be pressed partly into the surface and the surroundings will be pushed towards the rolls. The angle of the front side of the peak will increase and the rear side of the peak will not change. The peak can now be represented by two partly deformed and oppositely directed steps where the front side will form a crack (Fig. 10b) and the rear part a shingle (Fig. 10a).

The shingles, as seen in Fig. 8, are thus formed either from steps pointing in a direction opposite to the rolling direction (Fig. 10a) or from the rear parts of peaks (Fig. 10c). If the shingles are formed as suggested, the number of steps and/or peaks on the surface of the previous pass, (i.e. the first pass), should correspond to the number of shingles. Possible candidates are seen in Fig. 11, where large gorges resemble long steps in the surface, while cross hatches are similar to shorter steps. Peaks can be found as irregularities along the rolling ridges. These then result in a distribution of large and small shingles in the following pass.

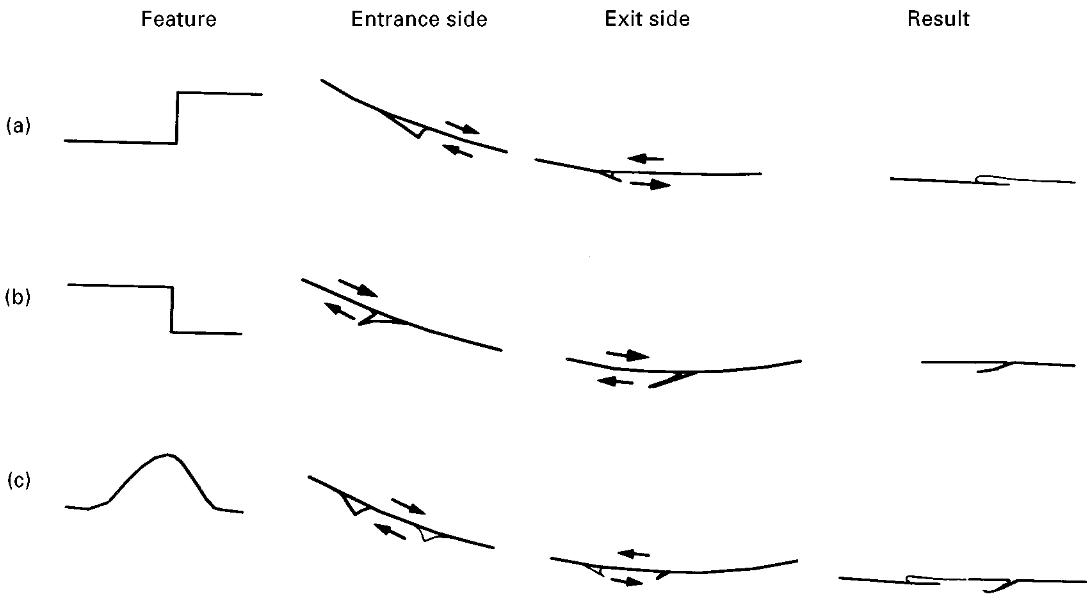


Figure 10 Sketch of how different shapes of surface irregularities (left) in longitudinal section respond to shear in the roll gap: (a, b) opposite directed steps, and (c) a peak.

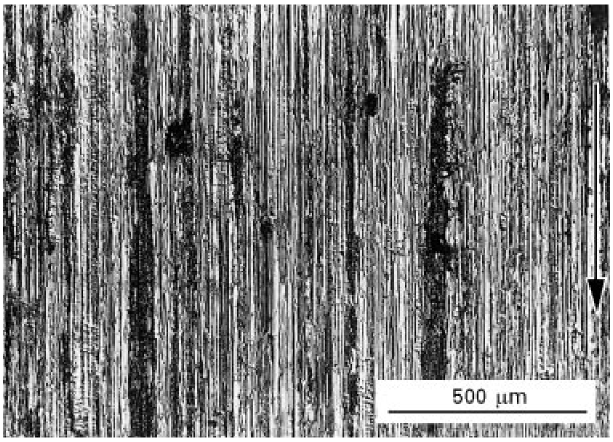


Figure 11 Optical micrograph of the surface structure of the first pass.

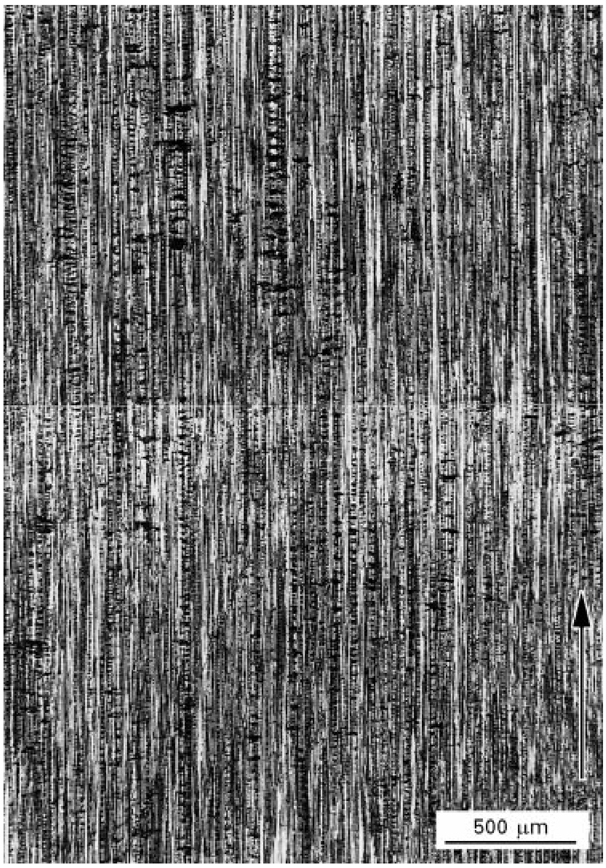


Figure 12 Optical micrograph of cross hatches in the sixth pass.

3.4. Formation of cross hatches

In the third and successive passes, numerous cross hatches are found along rows in large areas of the surface in an almost homogeneous manner (Fig. 12). The cross hatches observed in this work are mainly caused by laminated surface areas and not transverse fissures in the top of ridges.

Cross hatches in the laminated surface area appear generally in two different shapes:

1. Almost straight cracks normal to the rolling direction with a narrow opening compared with its width (Fig. 13a). These are found where the laminate adheres to the bulk sheet at both sides of the cracks.
2. Beak shaped cracks are formed in overhangs due to folding of ridges or shoulders of shingles (Fig. 13b), where only one side of the laminate adheres to the bulk sheet.

The cross hatches in the laminate are caused by stretching the surface more than the ductility allows. This excessive stretching can be caused by the material flow transverse to the rolling direction, because this movement is not so restricted, thereby leaving less volume to be elongated in the rolling direction. This is expected to give regularly spaced cross hatches to make up for the loss of material, in the same manner as the chevron phenomenon in extrusion. The

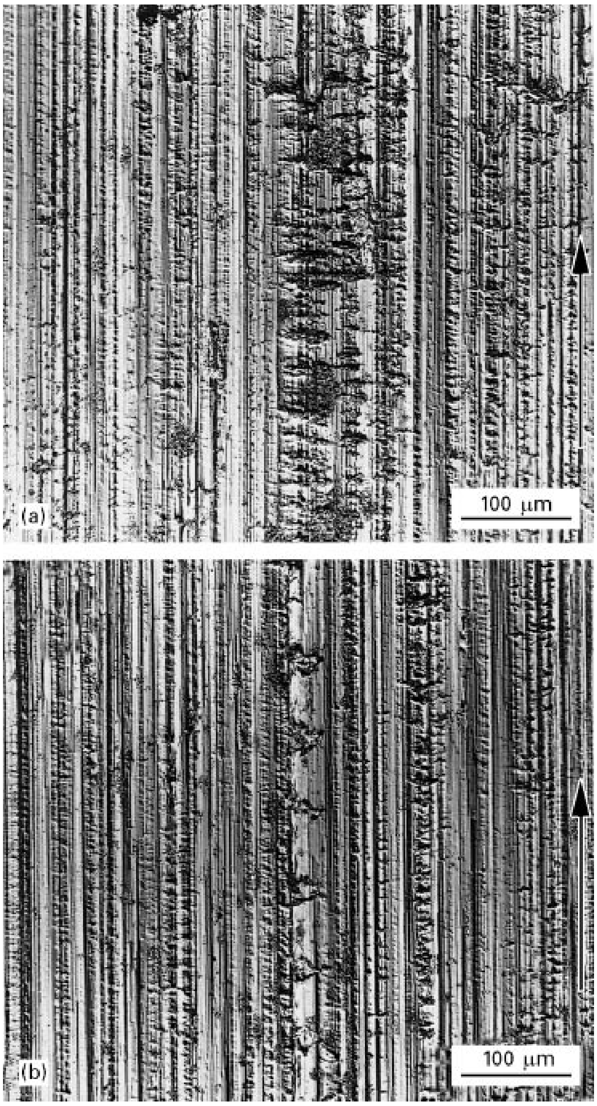


Figure 13 Optical micrograph of different types of cross hatches in the surface: (a) almost straight cracks normal to the rolling direction, and (b) beak shaped cracks.

cross hatches will appear earliest where the material flow is most easily directed in the transverse direction, which explains why the cross hatches are most often found on top of the rolling ridges.

Further rolling of the sheet will primarily widen the existing cross hatches. This is seen as an increase in both width and depth as the opening of the cross hatches grow. The distance between these widened cross hatches will increase in proportion to the extension of the sheet, which can be shown by Fourier tranformation for the almost straight cross hatches [7].

4. Conclusions

The present work has, based on observations of real industrial processed sheets and on verification experiments, revealed some of the mechanisms governing the deformation of the surface topography in the roll gap. The surface structure of the cast sheet is shown to be the main factor that governs the structure of the cold rolled sheet; this is comprised of:

1. Grooves–shingles
   - dominate the cast surface structure,
   - are produced by severe roughness peaks and valleys on the casting rolls, and
   - their sizes are determined at the exit side of the neutral plane.
2. Gorges
   - are deformed from initial pass grooves,
   - are long, narrow, steep sided with overhanging edges, and
   - have overhanging edges with regularly spaced cracks.
3. Shingles
   - are formed from large steps pointing opposite to the rolling direction and from the rear side of large peaks,
   - are smeared on top of existing surface forming interfaces below the upper surface, and
   - cause overlapping of different interfaces resulting in laminates within the surface.
4. Cross hatches
   - are torn in laminated surface areas,
   - grow in size and relative spacing as rolling proceeds, and
   - are also formed between existing cross hatches when strain induced by rolling exceeds what can be relaxed by exiting ones.

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