Process integration in the rolling of aluminium strip

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In all industries over the past decade, competitiveness has meant that meeting tighter tolerances, delivering on time and reducing costs has been the only way of staying in business. These trends in modern manufacturing approaches in the aluminium industry have tended to focus on each manufacturing unit independently and have certainly led to a more efficiency but also a degree of isolation of that unit from the process stream. This has reinforced a traditional view that certain key quality parameters are associated with specific process tasks, for example, the control of strip profile is a hot mill issue while control of flatness is a cold mill issue. While this approach allows each unit to gauge its performance, the lack of understanding of the importance of profile control (an upstream process) to finishing operations has prevented optimal final quality from being obtained.

From a customer perspective there are a few essential prescribed quality parameters: on-time delivery, mechanical properties, absence of surface defects, thickness tolerance, width tolerance and flatness. There are too the unwritten factors: runnability on their lines, appearance, technical understanding of the products' end uses, and of course cost.

Control of thickness

The strip thickness is measured at the exit side of most of the process steps in the production of aluminium in coiled form. The instrument used is commonly an X-ray system, chosen for its quick response time and low inherent noise. By applying the correct compensation for the environment in which the gauge is placed and allowing for the absorption characteristics of the alloy being rolled, the best automatic gauge control systems can achieve around 0.7% 3-sigma gauge variation around the target gauge through the coil length. This may seem to be well inside the specification for many products, but the thickness of the coil is not constant over the strip width. This variation in thickness across the strip width is defined as the strip profile and often characterised through two parameters, the crown (the difference in thickness between the edges and the centre-line) and the wedge (the difference in thickness between the two edges).

Impact of profile variation

When products such as can-ends are manufactured, which can be punched out from anywhere across the strip width, the overall variation in thickness as measured by the can-maker comes from both the variation over the coil length as well as over the coil width. This is illustrated in Figure 1. Thus both the gauge variation along the coil length and the contribution from the thickness change over the strip width need to be controlled.

The impact of profile can be seen more directly when a sheet of aluminium is slit into multiple reels. If there is a significant thickness difference over the strip width, the reels on the exit side of the slitter will exhibit different build-up rates, and therefore variable tensions in each reel. This is illustrated in Figure 2. Reels having a low tension are likely to collapse, and in so doing may also damage neighbouring reels. A technical solution to this problem is to use either looping pits to accommodate the extra length or tight-head slitters to accommodate the differences in tension, but these can only accommodate a limited range of absolute profile.

A more subtle effect of the profile can be seen in the way that flatness changes during the coiling of the strip. As the laps are laid on top of the spool, because the material is usually thicker in the centre than the edges, most of the load exerted towards the spool because of the tension on the outer lap is taken by the central part of the material and only a little of the load borne by the edges of the strip. This is illustrated in Figure 3. This radial pressure modifies the stresses of the material and creates internal stress differences. These stress differences can drive changes in the strip flatness. As has been demonstrated through mathematical models of the process, the key factors in this are the strip profile, the alloy and the thickness, the strip temperature and the coiling tension.

Causes of profile variation

There is of course a strong similarity in the way profile and flatness are dynamically controlled. Both are generated through a differential reduction of the strip passing through the roll gap. At the beginning of rolling, the ingot presented to a hot reversing mill is of uniform cross-section. However, the gap between the work rolls depends on many factors including the deflection of the rolls due to load, and the thermal and ground cambers that exist on the rolls. If the gap between the work rolls is not itself uniform, then the amount by which the strip is reduced across the width will be different. For thick hot material, lateral flow of the material can occur. Under these conditions the differences in strain that occur because there may be differential strain across the width are accommodated by producing a change in the cross-section, in other words, creating a strip profile.

As the material gets thinner, lateral flow becomes more and more restricted to the strip edges. The differential strain that is now occurring over the strip width can no longer be relieved by lateral flow. If the strains are large enough, they will cause buckling of the material. This buckling is a defect and is described as off-flatness.

If the profile of the material is to be controlled, there is in practice only a relatively small process window while the material is being reduced when changes in the cross-section are possible without creating off-flatness. This is shown in Figure 4. At relatively large thicknesses, the roll gap variations that are made across the strip width are small compared with a slab thickness. This means that the strip profile is not much altered. As the strip gets thinner, the actuators modifying the roll gap such as load and the coolant distribution become more effective. The actuators are most effective when the changes they produce in the roll gap form are comparable to that of the strip thickness. However the likelihood of buckling increases greatly as the strip gets thinner. Thus there is only a small regime when significant profile changes can be made without causing buckling. In aluminium rolling this regime is found at the gauges where in a conventional process route material is passing through the middle stands of a hot tandem mill.

In order to control best the form of the roll gap, the number of mechanical actuators available on mills has increased over the last decade or so. Six-high roll arrangements in mills with intermediate rolls that can be shifted as well as bent are now commonplace. Roll stack deflections (and the thermal contribution that they are designed to accommodate) are of course dependent on the alloy and the width but also strongly dependent on the pass schedule. The drive to increase productivity on the mill demands high reductions, and these lead to relatively large loads in the mills, generating large stack deflections as well as large thermal cambers on the rolls. The mechanical effects are controllable and predictable. Though possible to model, thermal changes are the most difficult to control when there are changes to the products being rolled or due to a roll change on the mill. These probably account for the majority of the variation in the profile of the coil.

Figure 5 shows the changes in Crown when the product width is changed. As can be seen, there is a large jump in the crown value at the transition between the two products and it takes several coils before the Crown value is restored to the target value. The Crown value is a convenient parameter with which to track the profile, but, as can be seen from figure 6 (taken from the paper by Herrmann et al 2006), it is not just the difference between the edge and the centre that changes but the whole profile form.

Controlling profile for a sequence of coils is now not so much about controlling the individual actuators but more a problem of providing the best setup for the stands on the rolling mill. As with any control system, if the setup is poor i.e. the actuators start some distance away from where they will finally end up, then it takes a control system some time to get to the final state and this introduces significant variation in the product. The emphasis today is on providing good setup models as well as recognising early any limitations or constraints on actuator movements.

Control of flatness

It is predominantly in the final cold rolling pass that the flatness of the delivered product is influenced. Flatness control utilises the same actuators in the cold mill as are used for profile control on a hot mill. It is therefore not surprising, that the ability to regulate the actuators is not the limiting factor for good flatness. The most difficult feature to control is the flatness of the strip edge. This becomes increasingly difficult as the materials get thinner, get harder or are rolled more quickly. Unfortunately these conditions are exactly those required to meet the demands of high productivity in rolling mills. Figure 7 illustrates the typical error in flatness that might be seen on the final pass. The very edge of the strip is significantly tight and there is a region close to the edge which is loose. Over the rest of the width of material the conformity to the target is good. There have been several attempts to improve on this. The use of additional actuators including intermediate rolls or shifting rolls and most of the mechanical actuators used in profile control have been tried for cold rolling. One of the biggest problems of using these additional actuators from the control perspective is that the characteristic of the actuators (the way that moving the actuators changes the strip flatness) overlaps. This makes it difficult to decide which actuator to move and how to stop the actuators from interfering with each other when attempting to correct flatness defects.

Latest thermal actuator

A technique commonly used in foil rolling has in recent years been applied to cold mills. This is the use of heated fluid applied beyond the strip edge. The reason the strip edge is tight relative to the rest of the strip is due to the steep thermal gradient that exists on the work rolls at the strip edge. This comes about because the heat from deformation and friction is transferred into the work roll over the strip width but some of the heat is conducted axially towards the roll ends. If the thermal gradient at the strip edge is greater than the relatively gentle gradients that can be applied by roll bending, the defect seen in figure 7 will arise. The application of a hot fluid outside the strip width mitigates this effect.

On a new cold mill with the full range of actuators plus the additional heating of the roll beyond the strip edge, it should now be possible to get the strip flatness to well within the customer specifications.

Integrating processes

A second process occurs during cold rolling. This is the winding of the material into coil form. As has already been described in the section under profile effect, this coiling process can change the flatness of the material. Flat material as measured from the strip exiting the cold mill bite, will not necessarily produce flat material in the final product at the customer. The way to ensure quality for the customer is to modify what is produced in the cold mill in such a way that takes into account the changes that are known to occur during coiling. This integration of the processes brings into stark relief the inter-dependency of profile and flatness.

Of course, during production internally or in the customer's location, there may be further process steps that could affect flatness. These include operations such as bending or straightening the material, heating it non-uniformly or cutting the material. Sometimes these operations are deliberately carried out to improve flatness for example when tension levelling is used.

Thus to meet the quality requirements of those aspects of the product that are frequently not written down, all the potential process steps need to be taken into account and their inter-dependencies understood. Without a good understanding of how the various stages in the production of aluminium affect the final product, optimum quality cannot be guaranteed. Process understanding is essential. It can be deduced by trying to understand from customers' complaints why material that is apparently near-perfect as it left the mill either can't run or runs poorly at the customers plant. It can also be learnt through courses that cover all the aspects of rolling, such as those provided by Innoval Technology Limited and other providers.

Some recent references

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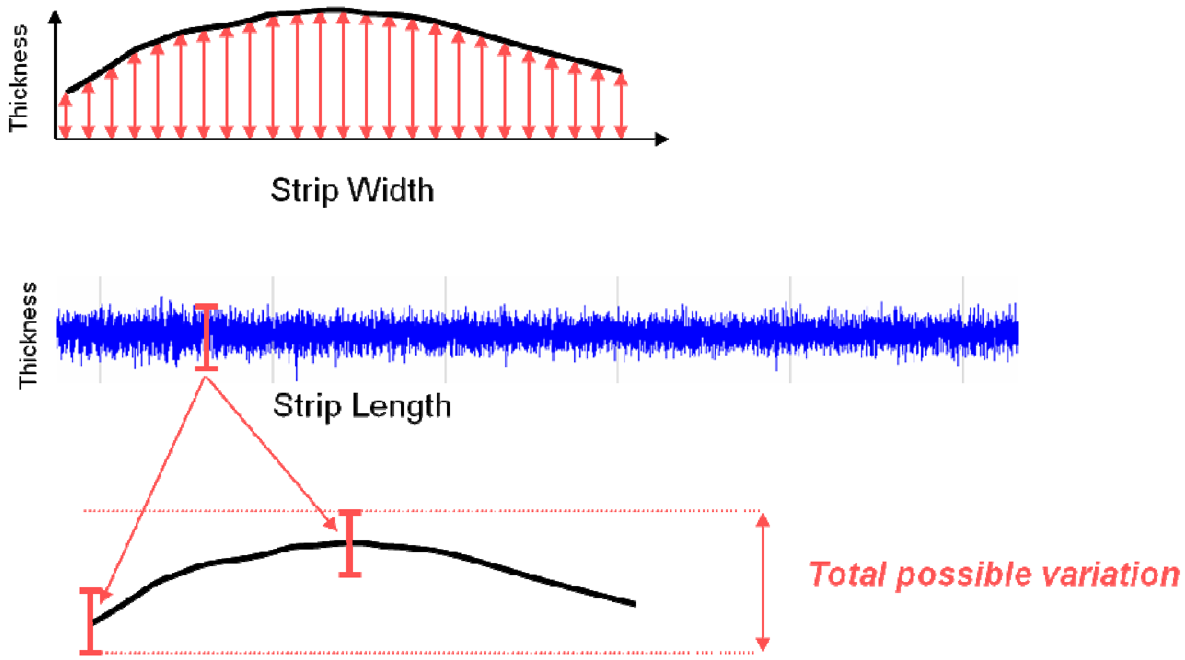

Figure 1 Makeup of total variation possible on coil thickness

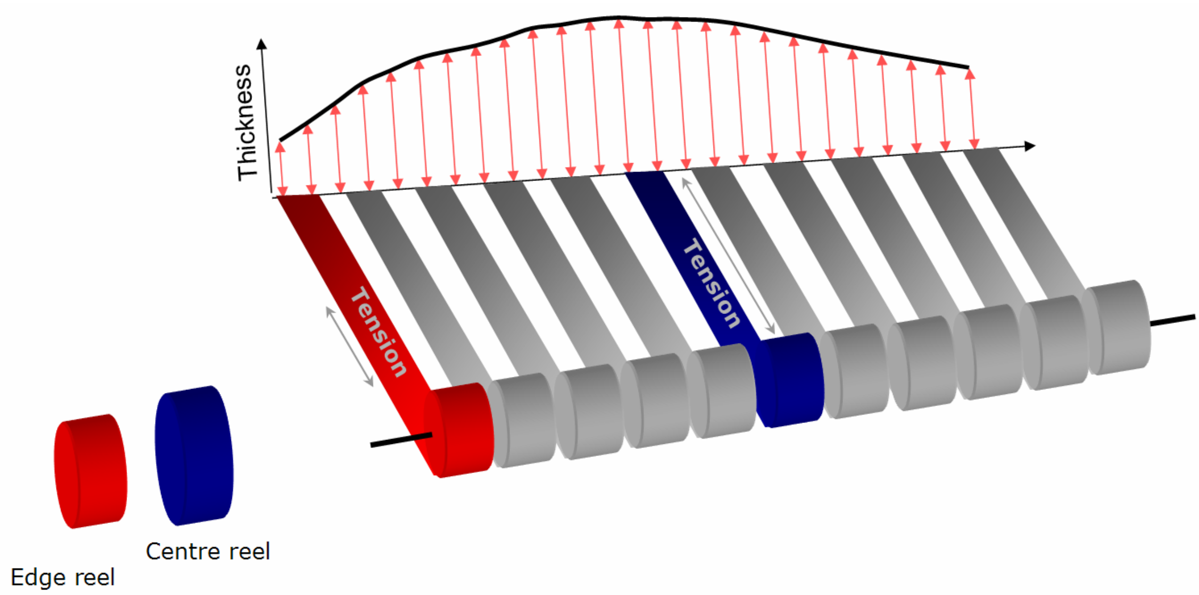

Figure 2 Impact of profile on multi-slit coils

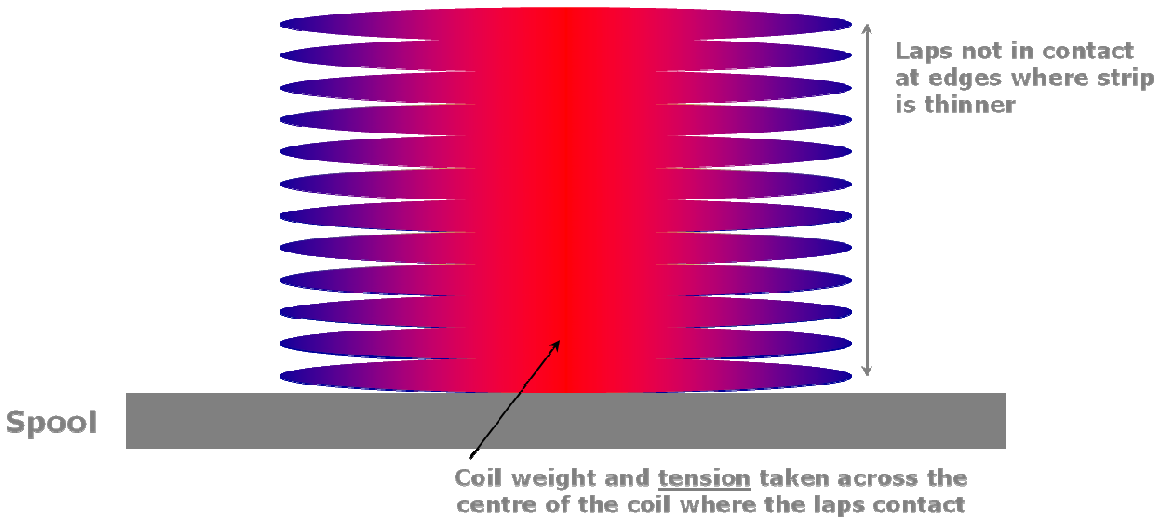

Figure 3 Schematic of how laps are built up while coiling

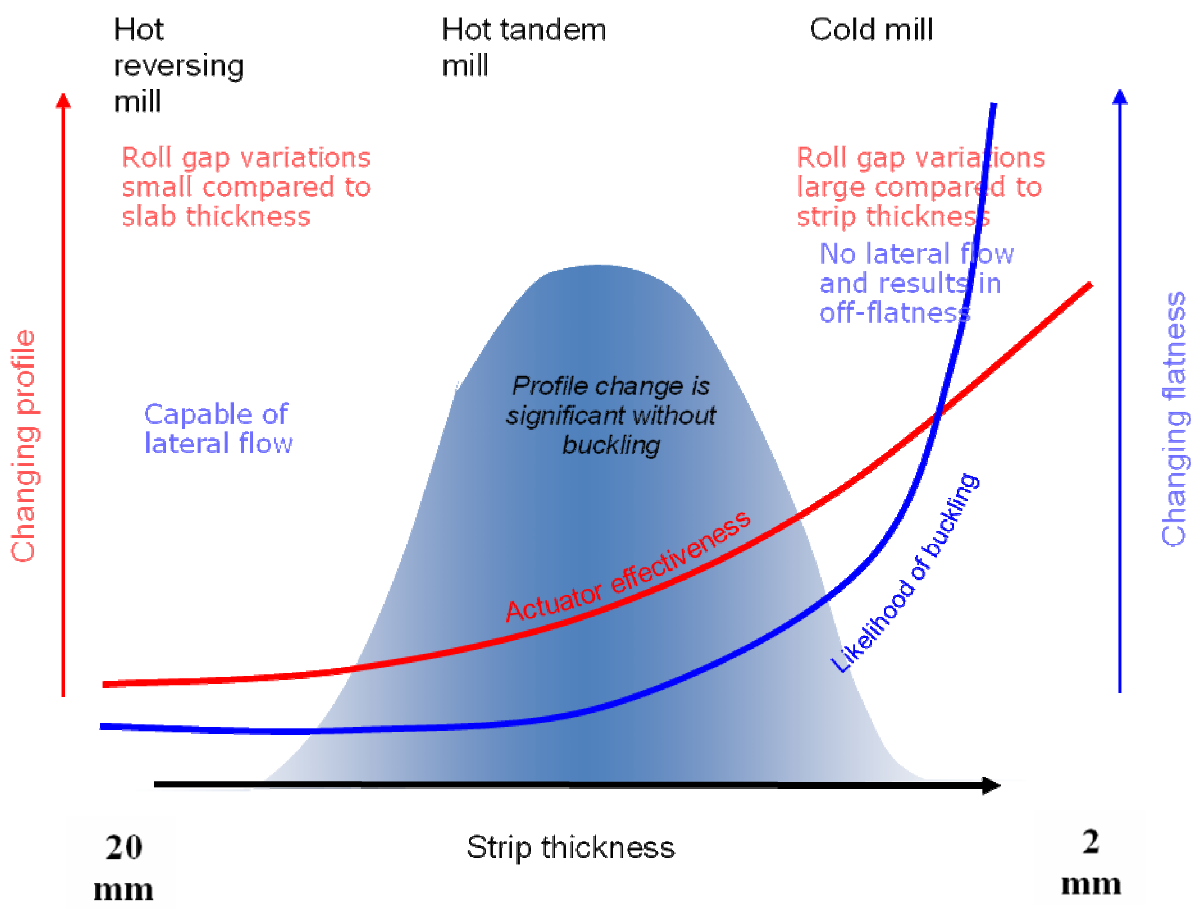

Figure 4 Dependencies on thickness of ability to change profile & likelihood of buckling

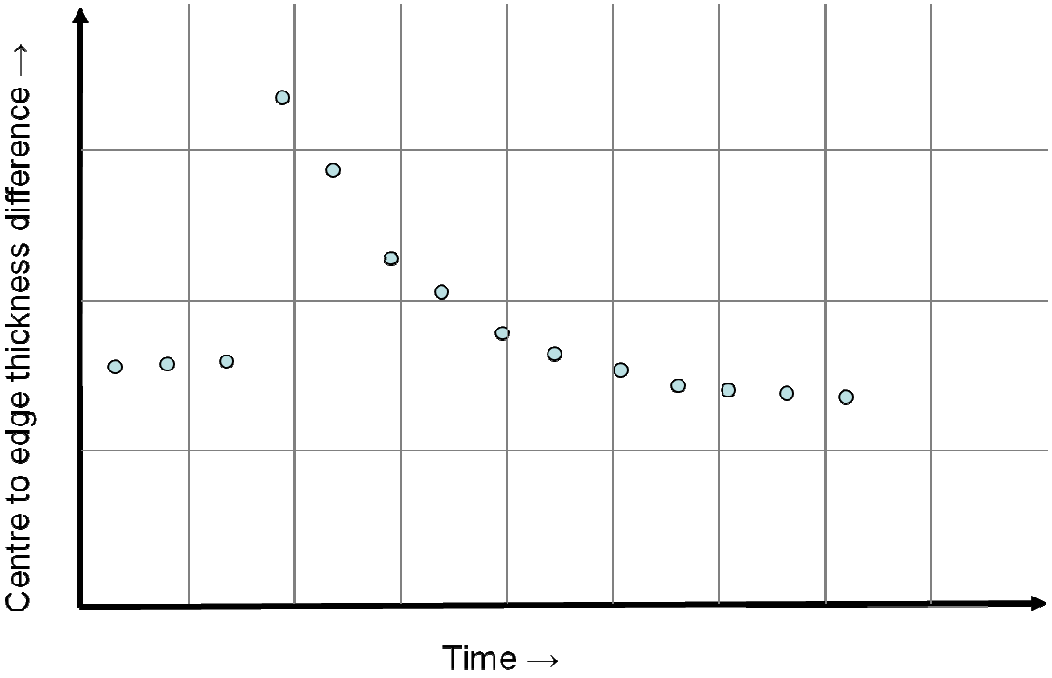

Figure 5 Transient in crown value caused by a product width change

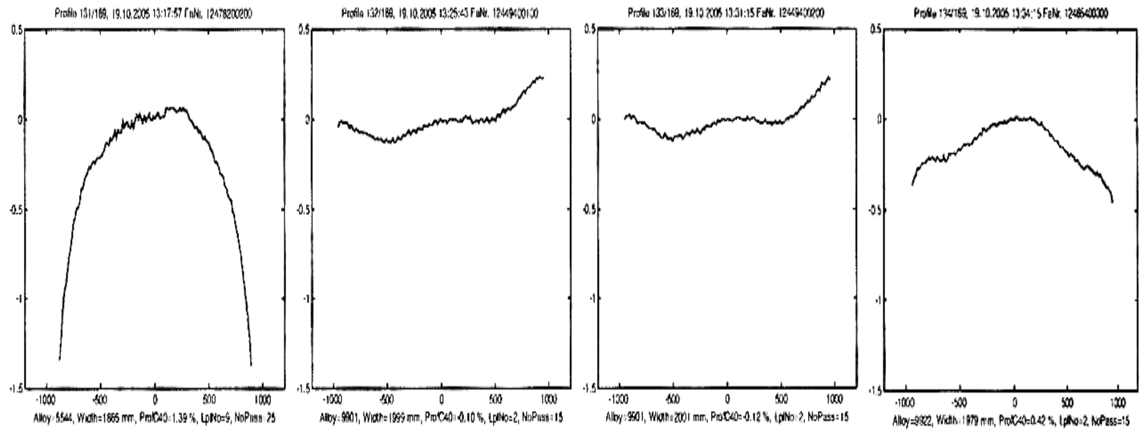

Figure 6 Profile measurements from a sequence of four slabs when changing from a hard to soft alloy (taken from paper by Herrmann et al, 2006)

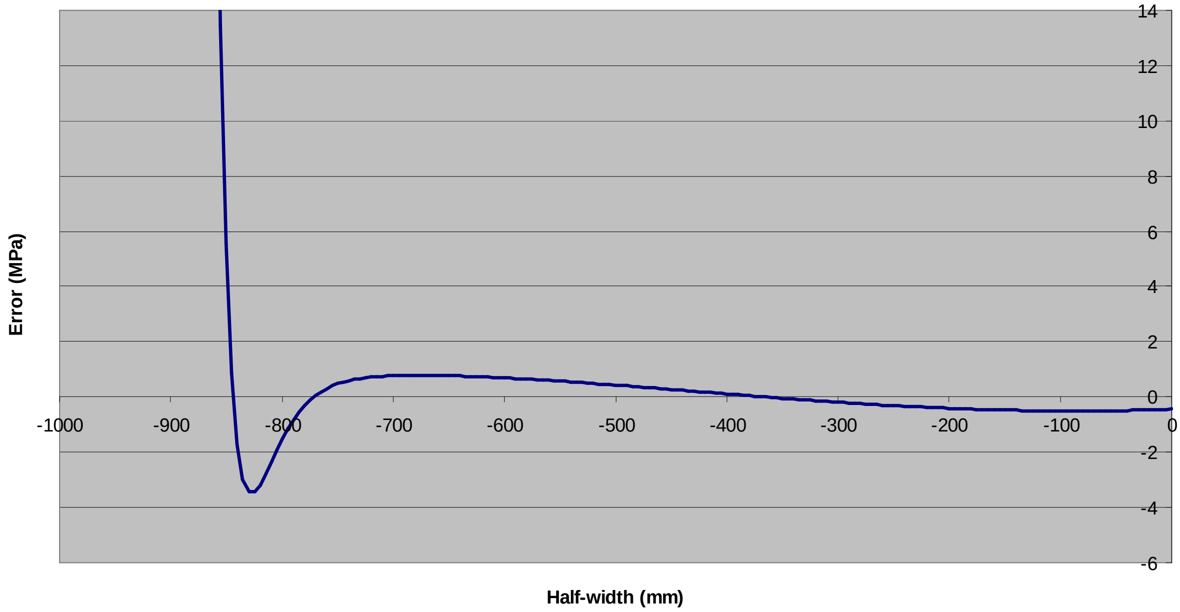

Figure 7 Typical flatness deviation from target (shown for only half the strip width)