Until comparatively recently, it has been convenient within our industries to treat profile and flatness if not as quite independent measures of material quality, then at least as separable measures. The emphasis today both from internal drivers, such as productivity & cost and external customer requirements, such as tighter specifications & longer lengths of defect-free products, means that this artificial separation is no longer possible. Faced with the challenges of emerging technical competencies from the so-called developing nations and the environmental and commercial requirements for husbanding the usage of energy it is timely to review the progress that has been made over the decade since the last conference was organised by the IoM on these topics and to set out some of the opportunities that still exist to solve the outstanding issues.

Definitions
Profile is the variation in strip thickness across the strip width. Frequently, the profile is characterised by a few parameters, such as the crown (the thickest part of the strip expressed as a percentage of the nominal thickness) and the wedge (the difference in thickness between the two strip edges). The variation near to the strip edge can be critical for subsequent processes and can be described through an edge drop parameter.

Off-flatness is the variation of free fibre lengths in the rolling direction across the strip width. Visually, it is the amount of buckling that occurs in a strip free of external tension. Flatness is conventionally measured in I-units which is a differential strain unit multiplied by 100000. This can be related to the buckling behaviour by the following formula, 
\[ \frac{\pi \cdot h^2}{2 \cdot d} \cdot 10^5 \text{ I-units} \]
where \( h \) is the buckle height and \( d \) is the distance between buckles. In the steel industry the steepness index, 
\[ \frac{h}{d} \cdot 10^5 \text{ I-units} \], is also used.

Why is profile important?
The strip profile is important as it has a significant impact on the downstream processing of coils, either in further plant operations or in manufacture at customers facilities. Strip profile influences the available process tolerance for products such as can-bodies that can be stamped out from any position across the strip width. Differences in thickness between the edge of the strip and the centre use up some of this available tolerance, requiring higher performance from centre-line and nominal gauge control systems. If the product is to be cut into strands and recoiled such as in fin-stock applications, then it becomes difficult to obtain good tensions for reels near the strip edges if the strip thickness at the edges is significantly different from that at the centre; the diameters of the reels at different positions across the strip width would naturally be different and so winding the reels at the same rate causes a drop in tension for the outer reels. Profile is also a major factor in determining the extent to which the coiling process changes the strip flatness.

What determines the strip profile?
Profile is determined through the form of the roll gap, which itself has contributions from the mechanical actuators, the rolling load (which is dependent on the product and the amount of reduction), roll flattening and the thermal condition of the rolls.

When rolling similar products in large batches on the mills, profile variation is small provide there are no significant time delays between ingots. However, frequent product changes are required by the demands of lean manufacturing and the pressure on high productivity rates. This means that the time for maintenance on mills is frequently reduced, resulting in mechanical or electrical breakdowns and
unplanned delays on the line. Changes in product or planned/unplanned delays result in profile variation; the larger the event, the larger the change in profile. Figure 1 shows the impact of a change in product width (wide to narrow) on the strip profile crown value. This is due to the effective mismatch of the existing thermal camber on the work rolls to that of the new product. The mechanical actuators are constrained in their ability to counter this effect because of their limited range and the need to avoid buckling of the strip.

![Figure 1 Change in strip profile of a sequence of coils due to a width change](image)

**Controlling profile**
Profile is controlled by altering the form of the roll gap during hot rolling. As is shown in Figure 2, there is a range of thicknesses for which changes in the roll gap are most effective. When the material is thick, for example during the reversing mill passes, mechanical actuators such as bending do alter the roll gap form, but the change is small relative to the strip thickness and so little impact is made on the strip profile. At thin gauges, when the roll gap form is altered, the local elongation differences of the strip caused by the strip experiencing differential reduction across the strip width cannot be accommodated and the strip physically buckles.

Controlling the strip profile during the rolling pass through feedback control is now feasible with the availability of X-ray profilometers whose time constants and noise characteristics are small relative to the previous generation of profilometers based on isotope sources. Because the thermal time constants during hot rolling are comparatively long, in-coil adjustment of the profile tends to be confined to the mechanical actuators. Accurate absolute gauge measurement requires knowledge of the material properties. Adaptive techniques are sometimes used to allow for changes in composition or in the different work-hardening behaviour of continuously-cast ingot compared to direct-cast material.

Control schemes may well be able to bring the profile within specification, but if the starting point is far from the target, a large proportion of the coil length may be outside tolerance. The further from target the profile is, the larger the losses while the profile approaches its target value.

Poor set-up is a major issue and this area has been tackled though advances in the modelling of the mills. Good set-up relies on accurate models. Modelling the mechanical actuators is straightforward and quick enough to be performed between coil changes. Tracking and verifying the thermal condition of the rolls is the most difficult task but as the profile transients are always thermal in origin, it is the most important one to address. Accurate modelling is also used to determine which of the available
actuators is best suited to obtain the desired strip profile, an especially complex problem when dealing with tandem mills.

**Controlling Flatness**

Improvements in flatness control have paralleled those in profile control (and the key issues seem to have the same root causes). There have been modest improvements in the mill measurement systems and the introduction of the first non-contact system. There has also been an extension of automatic flatness control (AFC) down to foil gauges, an area where it had been thought such systems could not be financially justified. There has been improved understanding of the non-linear impact of the conventional actuators (bending, tilt and distributed coolant control) on flatness and on-line models are now conventionally used in the modern systems to describe the transfer functions between the actuators and the strip flatness. There has also been the use of active backup rolls and other mechanical devices previously used for profile control. This employment of more actuators has led to the need to separate the functions of the actuators more clearly through multivariate transfer functions and so avoid the problems of two actuators tackling the same defect in opposition rather than cooperatively.

The proliferation of AFC systems has seen the productivity of cold mills improve dramatically, as the AFC in all but the final passes is used to produce strip flat enough to rewind buckle free, and generally free of the tight edge that gives rise to edge damage of the strip and to strip breaks. However the higher speeds and higher reductions have left most control systems struggling with a combination defect of a tight-edge coupled with a loose near-edge region on the strip. This is illustrated in Figure 3.

Over the last few years, a technique for solving this that started with foil mills has been applied to heavier gauge passes. Heated fluids are applied to the roll surface beyond the strip edge. This reduces or even eliminates the thermal gradient in the work roll near the strip edge position and therefore removes one of the causes of the tight edge in the strip. It is surprising that this approach known theoretically for many years, took so long to find application in cold mills for non-foil applications. This improvement has its greatest benefit on final passes in the process stream and not only allows higher productivity but also eliminates some of the surface defects associated with poor flatness.
As in profile control, the key areas still to be tackled consistently relate to transients on the mill. There are two other areas where AFC has been improved: threading and speed changes. Again, good setup predictions are essential if flat strip is to be obtained at all times from threading through acceleration up to run speeds. As control of thickness in finishing passes reflects the variation in thickness of the incoming material, good flatness can only be achieved if the incoming material is free of any large gauge excursions such as spikes. Any attempt by the gauge controller to make large changes immediately results in significant perturbations in strip flatness.

The drive from modern manufacturing techniques to reduce inventory and respond more quickly to the pull from customers also creates problems for flatness control. If the thermal cambers on a roll are mismatched to those needed for the product about to be rolled, it may be impossible to avoid flatness defects without resorting to tighter mill scheduling as is used on hot mills.

**Off-line Flatness**

Profile also contributes to off-flatness through what is now commonly termed ‘off-line’ flatness. On-line flatness is now reserved for the process of controlling the flatness in the mill, the domain of automatic flatness control (AFC) systems. During coiling (and cooling of the hot coil), changes in flatness occur driven by stress differences that develop as wraps under tension are wound on top the existing layers. The magnitude of the rewind tension is important, as is the profile of the strip. Profile cannot be changed during cold rolling, except through edge trimming, so achieving good consistent profiles during hot rolling becomes as important to flatness critical products as it is to thickness critical products. Even tension levelling is followed by coiling (except of course in cut-to-length lines) so the need to achieve the best possible flatness through the extensive use of better control schemes and an extended range of actuators on mills can be undone through the poor specification and control of strip profile.

It is now accepted that the delivered flatness is a combination both of the flatness achieved in the mill bite and that caused by subsequent processes with coiling as the main contributor.