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Definition of a New Parameter for Flatness Control in Hot Rolling Thin Metal Strip Production

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Key words: hot rolling, thin strip production, flatness control, flatness parameter, strip crown, flatness dead band, ECOV.

INTRODUCTION

Nowadays metal flat products, such as strips and plates, are widely used in many fields: buildings, transportation, automotive, food industry etc. The specific requirements of a metal strip or plate production are getting tighter, due to the explicit needs of the modern industries. For this reason improving the quality of the flat products is required. This improvement can be achieved by controlling the two main characteristics used to define a particular metal flat production: shape and flatness. In the last thirty years many efforts and studies were made in this way, leading to different kinds of partial solutions and precise theories that aim to achieve a perfect flatness and profile control system.

Flatness control must deal with a non-linear problem that it is the result of three physical phenomena, generally considered in the actual literature, to build mathematical and finite element models of the flat hot rolled products[1-2-3] . These phenomena are the thermal expansion of the rolls, their bending in conjunction with their elastic deformation and their wearing. Each one of these problems can be mathematically described by using non linear parametric equations and they all can be well simulated by using finite elements software.

Unfortunately in the real production many other factors concur to modify the expected flatness parameter of the final products, such as the non uniform thermal gradients of the rolled metal, the material anisotropy, the non symmetric position of the strip between the rolls, the non uniform wearing of the rolls, etc. All these details must be omitted in any mathematical model that is only a simplification of the reality, due to large quantity of data that should be used to completely describe a real physical mechanism and the consequent impossibility to compute them all in a time affective simulation.[4-5-6-7-8-9-10-11-12-13-14]

Many lines of investigation were followed to fill this gap between the real flat rolling production and the mathematical models. Fuzzy algorithms[15]-[16]-[17]-[18], transfer matrix based models[19], Artificial Neural Networks[20]-[21]-[22]-[23]-[24]-[25]-[26], non-linear Genetic Algorithms[27]-[28]-[29]-[30] - joined with results coming from the practice - are only some of the different kinds of studies undertaken.
In this article we adopted a different approach to the problem, starting from a mathematical relation deduced from the real practice of the hot rolling production, which can be summarized in the Flatness Dead Band theory. From this assumption we derive a new coefficient that we call *Exit Crown Optimum Values* (ECOV). By the mean of this unique data we can define for each stand of a hot rolling tandem mill the range of values of ECOV that can guarantee to obtain a flat strip. As it is explained in this article, the ECOV is an innovative coefficient not only because it summarizes a different approach to the flatness controlling problem, but even because it is easy to be calculated. ECOV essentially depends on the width and the crown at the exit of each stand of a hot rolling tandem mill, two parameters that can be easily measured by using a single shape gauge device, like an x-ray shapemeter.
Because in a thin strip hot rolling mill the finishing train is the one giving more problems regarding flatness control, we decided to focus our mathematical considerations only in this part of the thin strip production process.

STRIP FLATNESS AND STRIP CROWN

Strip crown and strip flatness are two basic parameters in the production of flat strips.

Strip crown – defined by equation (1) – is the difference between the center thickness and the mean of edge thickness for a flat rolled strip (fig. 1). It mainly depends from three factors: the thermal expansion of the rolls, the rolls wear and the rolls bending.

$$C = Y - \frac{(X_1 + X_2)}{2} \tag{1}$$

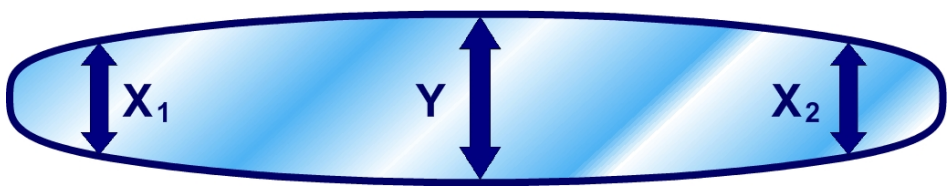

Fig. 1: Strip crown definition

Strip flatness - commonly expressed by I-unit and defined by equation (2) - is a term to quantify the waviness appearing on the strip surface (fig. 2).

$$I = \left(\frac{C_1}{h_1} - \frac{C_2}{h_2} \right) \cdot 10^5 \tag{2}$$

Where $\left(C_1 / h_1 \right)$ is the entry strip crown to entry thickness ratio in a rolling stand and $\left(C_2 / h_2 \right)$ is the exit strip crown to exit thickness ratio for the same stand.

Flatness is a parameters that it is much more difficult to be kept under control during the rolling process than the strip crown itself. The complexity of flatness controlling is connected to the fact that flatness depends on many different parameters which are difficult to be measured, particularly during hot rolling. In the last twenty years many different technologies and mathematical models were proposed to solve this problem. While the automatic strip width and gauge control reached great accuracy in guaranteeing strip quality, the flatness automatic control still lucks of precision, especially for the hot rolling process.
The causes at the base of strip flatness deviation can be subdivided in three main categories. The first and more important one is the non uniform elongation of the strip fibres along the strip length, because of uneven stresses acting across the strip width. When the internal stresses across the strip width are stronger then the latent forces - internal forces that contrast the appearing of waviness on the strip - a deterioration of the strip happens. In this case we speak of "strip manifest shape" and it can appear under different forms: i.e. strip camber, center waves, edge waves, quarter buckles, edge buckles, center buckles and so on.[31]-[32]
The second reason of strip waviness to appear is linked to the high rolling speed that sometimes can cause the strip to flutter. This anomalous movement of the strip can become visible like a uniform wave along the whole strip (up and down flutter) or like a waviness on the two sides of the strip not interesting the strip center (swing flutter).
The third source of strip flatness deviation does not have a mechanic nature, but it is linked to not even thermal gradients across the strip. This defect happens when we have a non homogeneous heating or cooling of the strip, with a consequent appearing of internal stresses that can locally overcome the yield stress of the material. In correspondence of these points we have a plastic deformation of the strip. Even if thermal gradients defects can be normally easily identified because of their peculiar

characteristics, sometimes - when they happen across the width of the strip - they can be confused with edge waves or edge buckles, leading to difficulties in controlling them.[33]

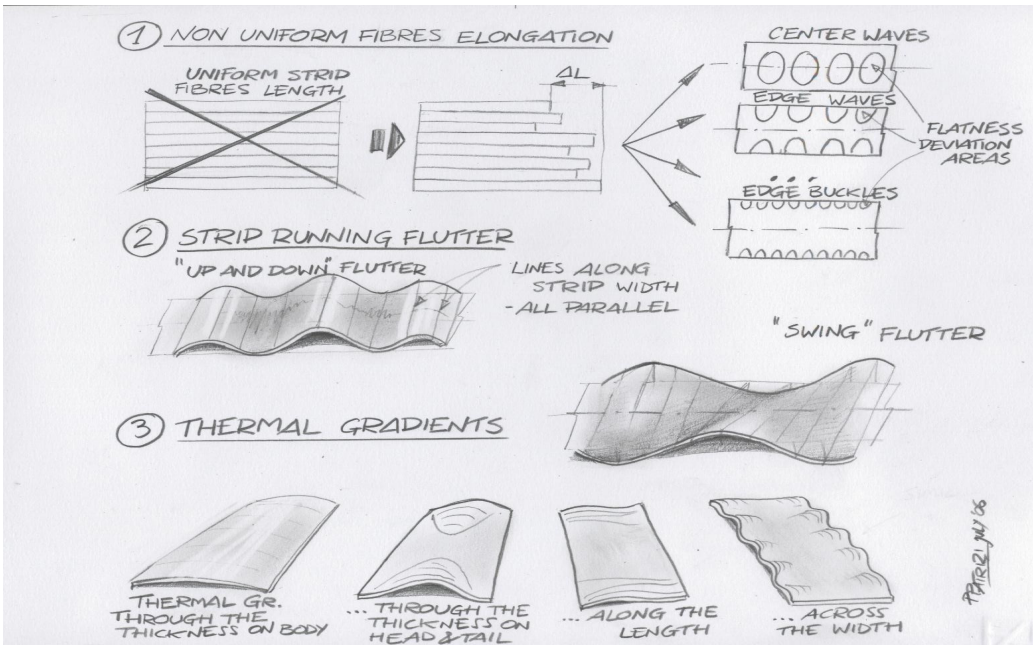

Fig. 2 – Causes of flatness deviation

From the nature of the strip waviness we can comprehend that these defects are hard to be controlled, especially when we have to deal with really thin strips, where a difference in fibres elongation above 0.01% can be enough for superficial defects to appear: i.e. for a 1 mm thickness strip we should be able to spot a variation in fibres length of 10 μm.

FLATNESS DEAD BAND

Strip crown and flatness are mutually related and their values must be taken under defined limits in consideration of the specific production. To understand the relationship between strip crown and strip flatness we have to consider that only for a certain working roll crown we can obtain an ideal flat strip with a defined strip crown. During the rolling process it often happens that the working rolls crown changes, mainly due to the rolls temperature - that slightly inflates or shrinks the rolls - the rolls wear and the rolls bending, thus producing a change in the strip crown that leads to an uneven thickness reduction. This non uniform thickness reduction causes an uneven longitudinal stretch of the strip fibers that we identified as the main reason of waviness on the strip.
One mathematical expression of strip crown and flatness correlation comes from the practical experience of the flat rolling plants and it is typically defined by the model developed by Shohet and Townsend[34] and further studied by Somers[35]:

$$-80\left(\frac{h_2}{w_2}\right)^a < \delta < 40\left(\frac{h_2}{w_2}\right)^b \tag{3}$$

- h_2 is the strip thickness at the exit of the rolling stand and w_2 is the correspondent strip width;
- *a* and *b* are empirically defined and they have different values for the different plants, but in this paper we give them both a value equal to 1.86, according with Somers;

δ is the so called *per-Unit Crown Change,* which formally declares the different strip fibers elongation along its width and it, is expressed by:

$$\delta = \left(\frac{C_1}{h_1}\right) - \left(\frac{C_2}{h_2}\right) \tag{4}$$

When $\delta < 0$ the strip tends to develop edge waves, when $\delta > 0$ center waves tend to appear on the strip surface. However, inside the range of values of δ defined by equation (3), we don't have any worsening of the strip flatness. If we plot the thickness to

width ratio against the per-unit strip crown change (Fig. 3), it is possible to see that the good values of δ are inside a defined area of our graph, that is known as *Flatness Dead Band* (FDB).

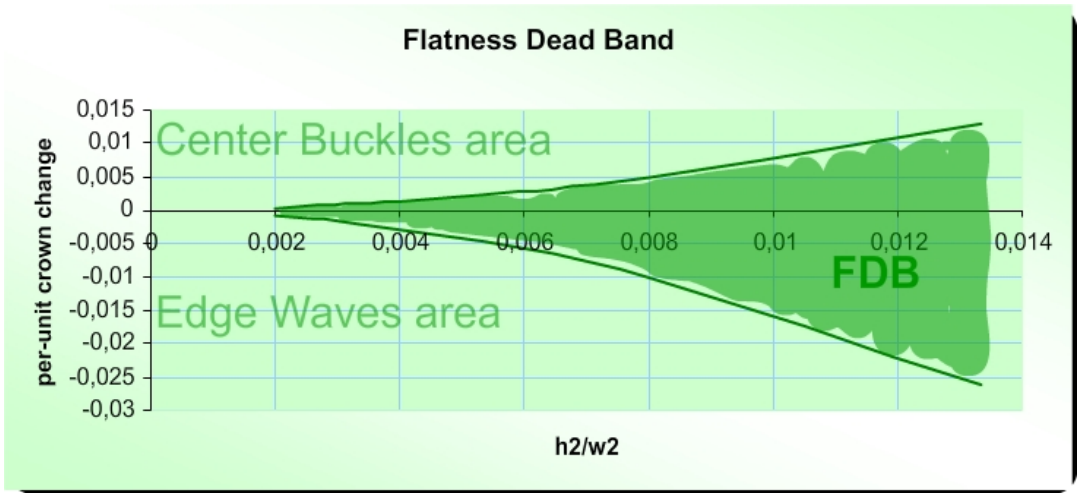

Fig. 3: Flatness Dead Band (FDB) representation

It is furthermore interesting to plot the values corresponding to different rolling stands of a finishing rolling mill, to better understand that the strip flatness is as much harder to be achieved as smaller the thickness gets (Fig. 4). The data represented in figure 4 are those of a 1700 mm 6-stand hot strip finishing mill. The strip is rolled from stand F1 to stand F6, with the higher relative thickness reduction happening on stand F1 and the smaller one on stand F6. It is easy to see that from F1 to F4 the strip per-unit crown change is in the FDB values, while for F5 and F6 the strip tends to develop center buckles.

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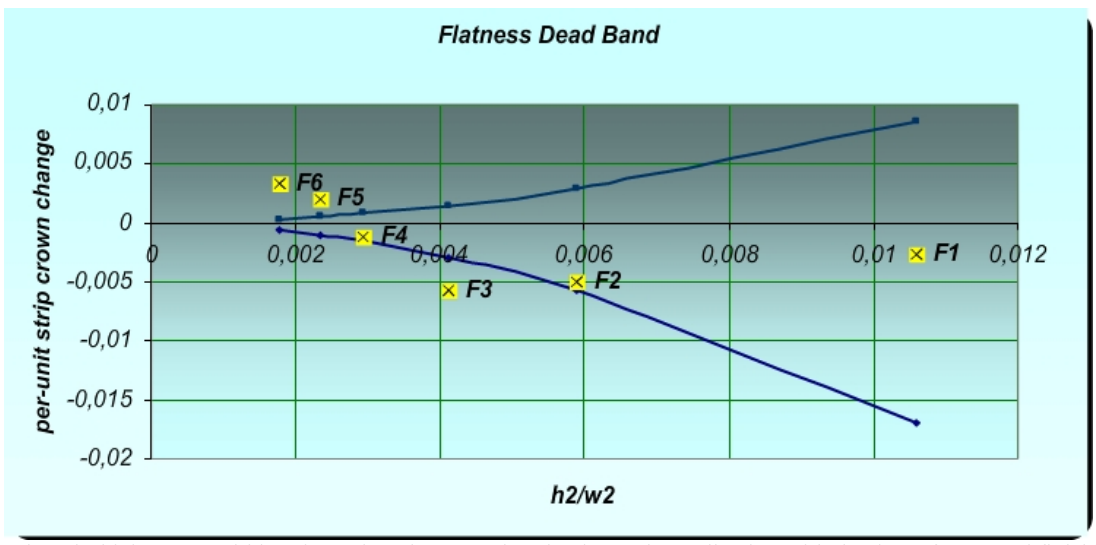

Fig. 4: Strip exit thickness to width ratio against the per-unit strip change in application with the data of a 6-stand finishing mill 1700 mm hot strip mill

For a flat strip production it would be important to fit all the rolling values, from F1 to F6, inside the FDB. In other words flatness is related to minimizing the value of δ .

STRIP CROWN AND STRIP FLATNESS RELATIONSHIP

To better understand the dependence of flatness to the strip crown, we made some considerations on the FDB expression. From equations (3) and (4) it is possible to write that:

$$\frac{C_1}{h_1} - \frac{C_2}{h_2} > -80\left(\frac{h_2}{w_2}\right)^a \tag{5}$$

$$\frac{C_1}{h_1} - \frac{C_2}{h_2} < 40\left(\frac{h_2}{w_2}\right)^b \tag{6}$$

In consideration that h_1, h_2 and w_2 are defined for the specific production, as well as the coefficient a and b that we suppose equal to 1.86, from equations (5) and (6) it is possible to write a two expression for C_2 as function of C_1, thus $C_2 = f(C_1)$:

$$C_2 \min = C_1 \frac{h_2}{h_1} + 80 \cdot \left(\frac{h_2^{a+1}}{w_2^a}\right) \tag{7}$$

$$C_2 \max = C_1 \frac{h_2}{h_1} - 40 \cdot \left(\frac{h_2^{b+1}}{w_2^b}\right) \tag{8}$$

where $C_2 \min$ and $C_2 \max$ are the minimum and maximum values of the exit strip crown, for each rolling stand, in consideration of the boundaries given by the FDB.
We furthermore plotted the variation of $C_2 \min$ and $C_2 \max$ for a range of possible values of C_1, shown on figure 5. To keep the graph clear only the data for the first three stands are plotted.

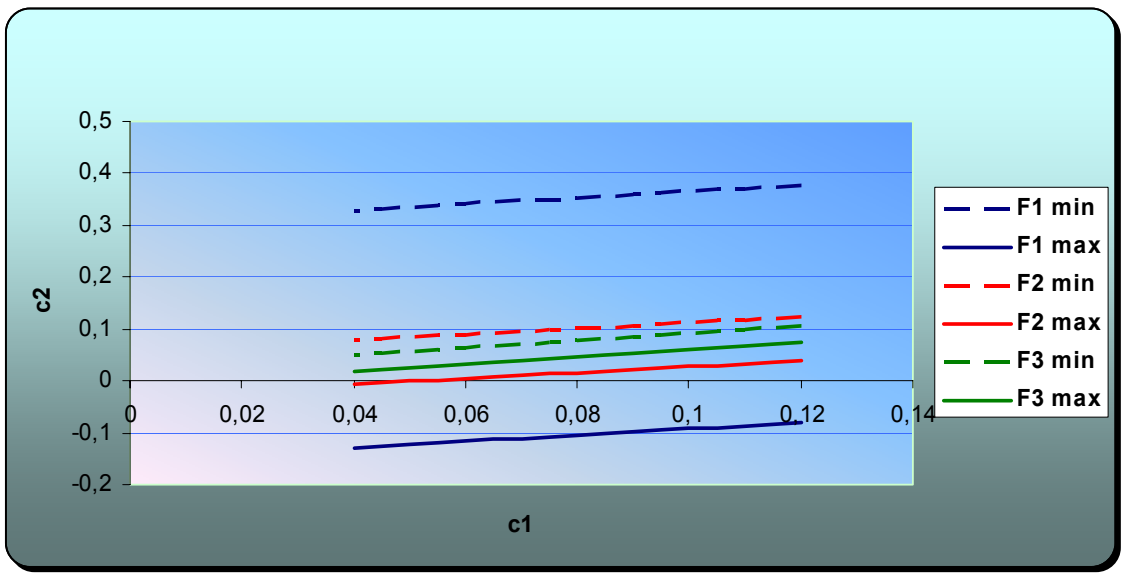

Fig. 5: minimum and maximum values of the exit strip crown as function of the entry strip crown calculated for the first three stands

For each stand the dotted line represents the values calculated from equation (7) - $C_2 \min$ - and the straight line the ones calculated from equation (8) - $C_2 \max$. The rectangular area - that we call *Optimum Exit Crown Area* (OECA) - enclosed between these two lines represents all C_2 solutions that satisfy the FDB criteria, thus the values of C_2 that can assure the flatness of the strip for the range of C_1 considered i.e. the OECA defined by F1 min, F1 max, C_1 minimum and C_1 maximum contains the admissible values of the exit crown for the F1 stand to obtain a flat strip. As we could have supposed the OECA gets smaller going through stand F1 to stand F6 (on figure 5, for scale reasons, only the OECA of the first three stands are plotted).

In addition, from figure 3, it is possible to notice that the plotted lines are all parallel one to another. This means that for a single stand and for any C_1 the range of optimum values of C_2 is constant. In other words, to assure the flatness of the strip it is not important which is the entry strip crown value, but keeping under a certain range the exit strip crown value.
We define this range of crown values as *Exit Crown Optimum Values* (ECOV). The ECOV can be univocally calculated for each stand of a specific production, where h_2 and w_2 are given. Mathematically we can define it as:

$$ECOV = 40 \cdot \left(\frac{2h_2^{a+1}}{w_2^a} + \frac{h_2^{b+1}}{w_2^b} \right) \tag{9}$$

It is significant to notice that ECOV depends only on the exit thickness, the strip width and the coefficient *a* and *b*. A clear representation of the ECOV distribution obtained for a 1700 mm 6-stand hot strip finishing mill is given on figure 6 and 7.

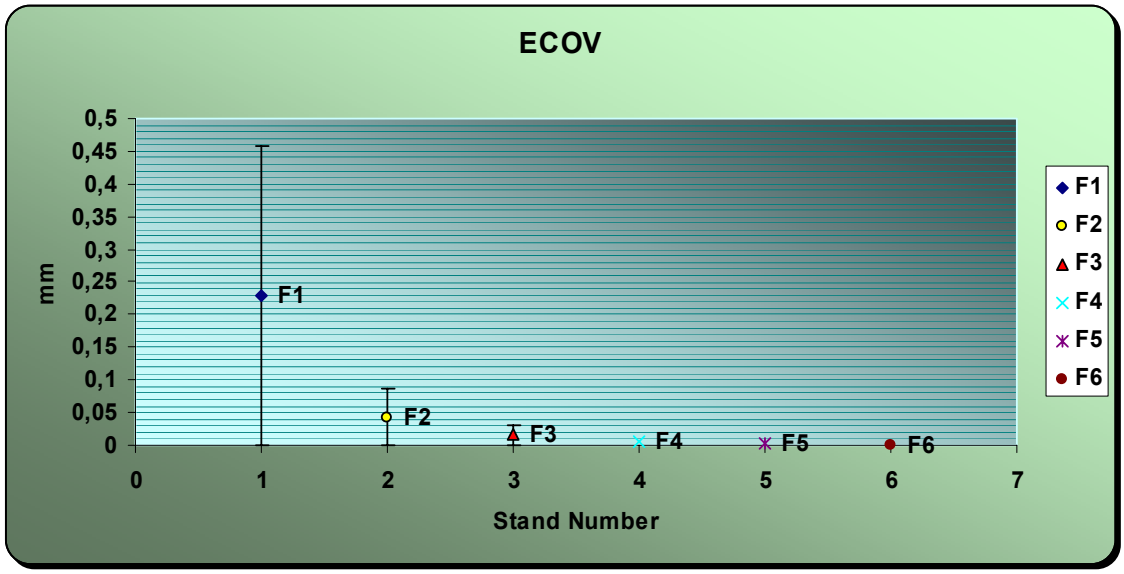

Fig. 6: ECOV values representation for each stand of a 1700 mm 6-stand hot strip finishing mill

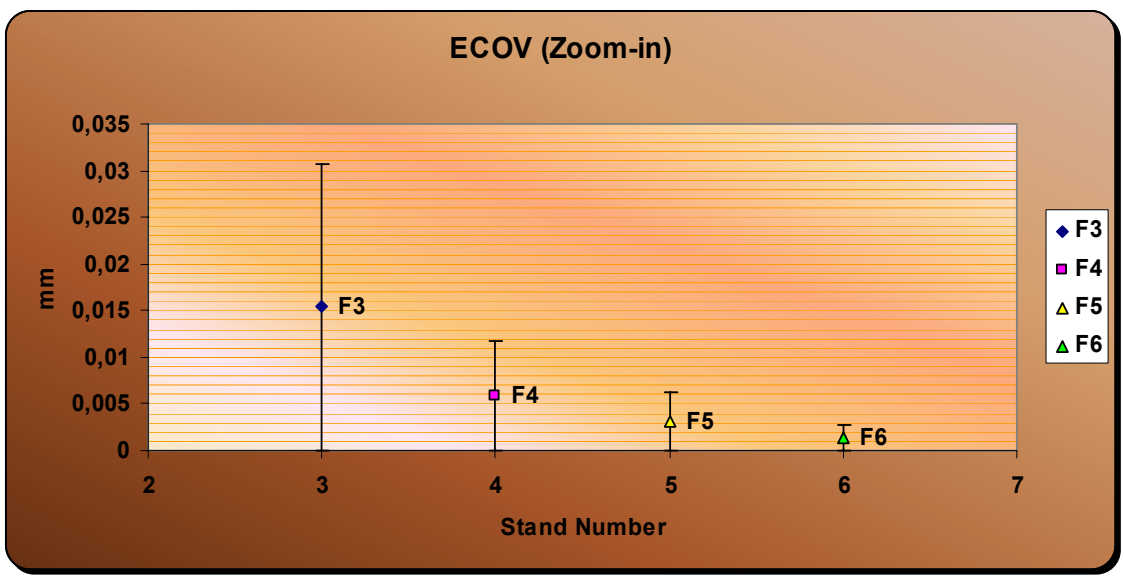

Fig. 7: ECOV values representation for each stand of a 1700 mm 6-stand hot strip finishing mill – Zoom-in from figure 6 to better understand the range of values of the last three stands

On figure 6 it is possible to see the actual proportion of the different ECOV for the six stands of the specific rolling train, while on figure 7 only the last four stands (F3, F4, F5 and F6) are considered, due to scale problems.
Finally it is interesting to plot how the ECOV changes by changing the width of the strip (Figure 8). This is useful because it often happen to produce a metal strip of different widths but of the same thickness.

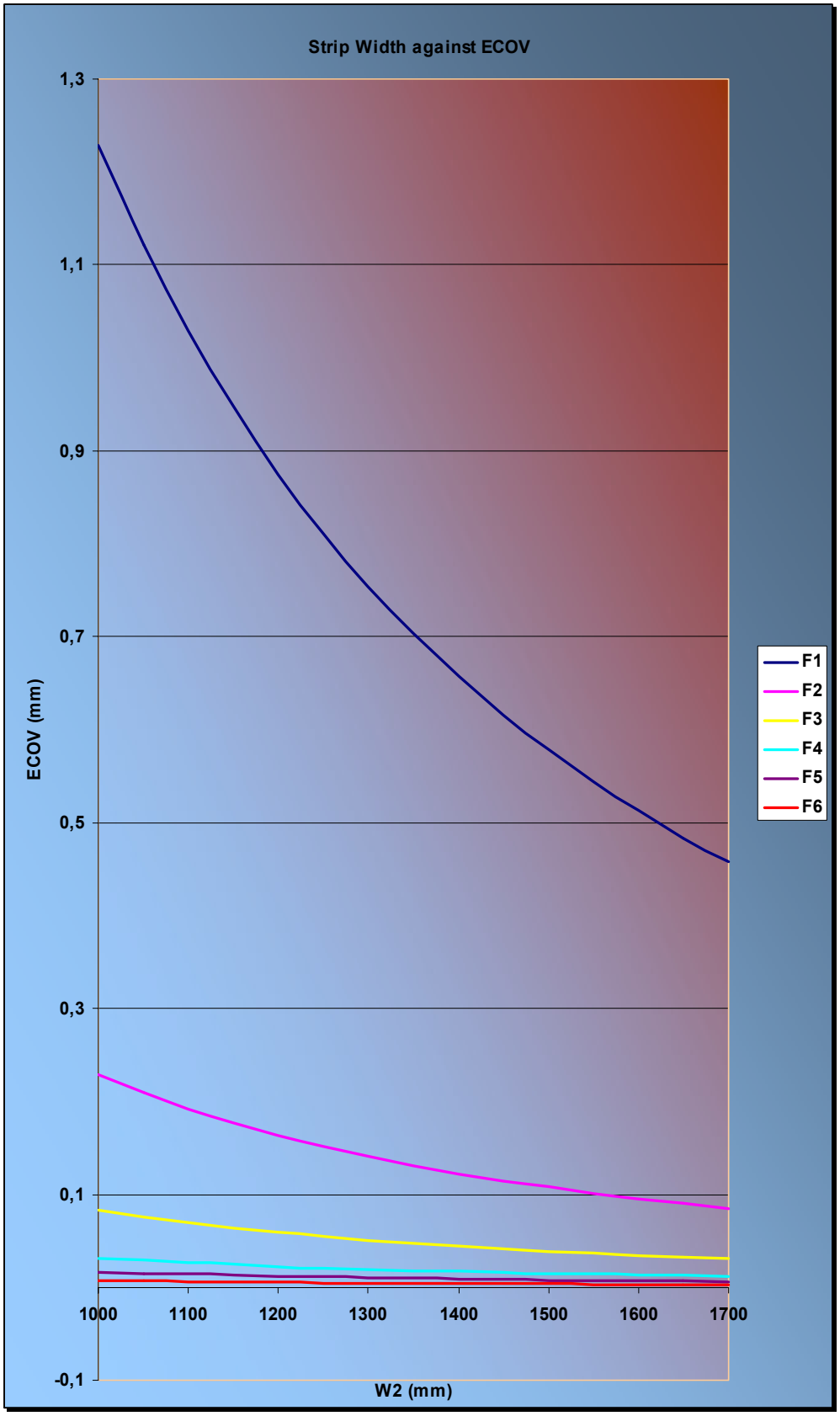

Fig. 8: variation of the ECOV by changing the width of the metal strip

As we could have expected the ECOV gets bigger by reducing the strip width: from the actual experience it is much more difficult to produce a flat strip with the increasing of the strip width. This last result is also important to demonstrate the consistency of our considerations with the problems encountered in the real production.

CONCLUSIONS

Flatness in metal strip production is a parameter difficult to be kept under control and it is also directly linked to the quality of the strip itself. To have an idea of the conditions that are essential to obtain a flat strip, we considered the empirical equation that it is at the base of the Flatness Dead Band. Starting from this definition we demonstrated that - for a specific production of a 6-stand hot strip finishing mill - flatness can be explained only by the value of the strip crown at the exit of each stand. If the exit crown considered is inside a specific range of values, that we called ECOV (Exit Crown Optimum Values), a good flatness of the final strip can be achieved.
This work aims to give another point of view on better understanding the parameters that are at the base of the strip flatness by minimizing the dependence of the strip flatness to a unique factor (C_2). As a direct result it could be much easier to realize new automatic flatness control systems.

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