

# OPTIMIZATION OF ROLL MECHANICAL PROFILES IN A CONTINUOUS ANNEALING LINE FOR STEEL STRIPS

by

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## ABSTRACT

In order to set the mechanical characteristics to the target of the customer, cold rolled steel strips are annealed at high temperature in batch or continuous annealing furnaces.

In a continuous annealing furnace, the strip passes over thermally deformed rollers. The shape of the furnace rollers at high temperature depends on this thermal deformation and on a mechanical profile on the roll. An accurate setting of the mechanical roller profiles is of major importance in order to avoid tracking problems, specially in the first part of the furnace, or buckling problems when the strip is wide and processed at high temperature.

Since the last 15 years, the part of the strips processed in the continuous annealing lines is dramatically increasing in the world; the products are also getting thinner and wider and the processing speeds higher, causing lateral strip displacement and strip deformations, like buckles, more critical.

In this context, it was important to accurately estimate the thermal deformation of the rollers and the critical conditions for buckling. IRSID and SOLLAC developed calculation models of roller thermal expansion, and wrinkling criteria. Those models were used to set new values of mechanical profiles for rollers in the annealing furnaces of SOLLAC.

## NOMENCLATURE

- D roller diameter, mm
- Kc heat transfer coefficient between strip and roller, W/m<sup>2</sup>K
- Ra roughness, μm
- t thickness of the strip, mm

$u_x$	displacement of a strip element in the X direction
$u_y$	displacement of a strip element in the Y direction
$u_z$	displacement of a strip element in the Z direction
$w$	width of the strip, mm
$w_{fp}$	width of the flat part of the roller, mm
$w_r$	total width of the roller, mm
$\Delta h$	taper of the roller, mm
$\sigma_t$	uniform tensile stress applied to the strip, Mpa
$\sigma_x$	stress in the machine direction, Mpa
$\sigma_y$	stress in the transverse direction, Mpa
$\theta_x$	rotation around X axis
$\theta_y$	rotation around Y axis
$\theta_z$	rotation around Z axis.

## INTRODUCTION

In most continuous annealing lines for steel strips, the strip is heated in a heating section at a temperature of 700 to 800 deg with radiating elements. The strip is treated for about 30 seconds at this temperature. The strips are then cooled down to a temperature below than 50 deg. (figure 1). The maximum processing speed is in SOLLAC 250 m/min for thin sheets (thickness higher than 0,4 mm) and 670 m/min for tin plate (thickness below 0,4 mm).

In the heating section, the radiating elements heat the strip, but also the rollers (figure 2). As the center of the roller is in contact with a cold strip and cooled, a temperature difference between the center and the edges of the rollers is generated. This temperature difference causes less thermal expansion at the roller center (figure 3). This effect, depending of the roller shape, might even lead to a concave shape and therefore the strip might get laterally displaced or buckled.

Since years, it is practiced to provide shapes to rollers to compensate for thermal deformation so the strip stays in line.

Today, increased speed, wider and thinner strip processed cause strip handling problems, specially wrinkling. IRSID investigated the thermal deformation of the rollers in the furnace and studied the wrinkling problem, in order to set more accurately the roller profiles for annealing furnaces of SOLLAC.

## MODELING THE THERMAL EXPANSION OF THE ROLLER

The amount of thermal deformation depends on the furnace, roller and strip characteristics and is calculated with a thermal model coupled with a mechanical model (figure 4). The thermal model predicts the temperature difference on the roller as a function of the strip, the roller and the furnace characteristics. This temperature difference is the input of a mechanical calculation that predicts the thermal deformation of the roller, and the real shape of the roller, resulting in the addition of the initial shape and the thermal deformation.

### **Thermal model [1]**

The thermal model inputs the strip characteristics (width, thickness, temperature), the roller characteristics (emissivity, conductivity, specific heat, density), the transfer coefficient between strip and roller and the radiating element temperature.

The temperature distribution on the roller is calculated with a finite difference model of conduction in the roller that has been developed in IRSID (figure 5). The roller is considered to be homogeneous and symmetrical and conduction in the radial as well as in the transverse direction is implemented. Radiation inside the roller contributes to increase the conduction in the transverse direction. The edges of the roller are considered to be thermally isolated. This is theoretically not true because conduction in the roller creates also a heat transfer through the shaft outside the furnace wall. But the influence is not critical for our further investigation.

This models inputs the thermal flow between the radiating element and the edges of the roll, and between the strip and the center of the roller. These flows are calculated under several assumptions as described above.

**Heat flow on the edges of the roller.** The radiating elements temperature is homogeneous.

**Heat flow on the center of the roll.** The part of the roller considered is the contact area of the strip (figure 5). In this area, the strip temperature is determined and homogeneous. The radiating element heats up the roller surface, which transfers heat to the strip. As the contact time of a strip element is very short, there is practically no change of the strip temperature. As half of the roller is always in contact with the strip, there is a significant influence on the roller temperature (depending on the strip temperature and on a transfer coefficient between the strip and the roll).

### **Experimental results**

One of the major problem to solve was to set the transfer coefficient between strip and roll. Literature gives the value of  $1600 \text{ W/m}^2\text{K}$  for a perfect contact between two solids made of steel. In the case of a strip wrapped around a roller in a continuous annealing line, the contact pressure is very low (approximately of  $10^{-3}$  to  $10^{-4}$  Mpa) and the roughnesses of the two surfaces influence the contact (typically a roller has a roughness of 4 to 10  $\mu\text{m}$ , and the strip of 0,3 to 2  $\mu\text{m}$ ).

These particular conditions of contact can lead to a significant change on the transfer coefficient. In order to check this influence, experimental measurements of roller transverse temperature were made on the low scale continuous annealing line of the CRM (Centre de Recherche Métallurgiques, Liège, Belgium) with a scanning optical pyrometer, in a heating chamber equipped with heating resistors.

Figure 6 shows the results obtained for a 300 mm wide strip, processed on a 350 mm wide roll. The strip temperature is 577 deg. The furnace temperature is 783 deg. and the temperature difference between the center and the edges of the roller is approximately 50 deg. This value is low because the strip is wide compared to the width of the roller and the radiating flow coming from the heating resistors is applied to a very small surface of the roller.

The calculation shows that the theoretical result fits to the experimental result for a heat transfer coefficient of  $160 \text{ W/m}^2\text{K}$ . For the value of  $1600 \text{ W/m}^2\text{K}$ , the heat flow from the strip is overestimated and the calculated temperature distribution is underestimated.

### **Prediction of deformed shape of the roll**

The temperature difference is the input of a mechanical FEM calculation made with the code SYSTUS that predicts the thermal deformation of the roll. For calculation reasons we made the assumption that the center of the roller stays fixed in line while half of the roller is laterally expanding.

Figure 7 shows the thermal deformation calculated for two strips processed at maximum speed at a roller in the heating section of the continuous annealing line at SOLLAC Mardyck (north of France). It can be noticed that the strip temperature distribution depends on the strip width. In both cases, the total strip temperature difference between the center and the edge of the roller is about 200 deg. and the total radial thermal deformation is about 1,3 mm.

When the width of the strip processed is increasing, a part of the roll, located between the edges of the two strips, will see an important difference of temperature and, as a consequence, a variation of the thermal deformation. The magnitude of this deformation is significant for steel strips behavior in the furnace in stable and in transient running, and influences the design for optimum roller shape.

As an example, figure 8 and 9 show the shapes of the roller at high temperature for two initial roller shapes (flat part  $w_{fp} = 350$  mm and taper  $\Delta h = 1,5$  and 3 mm). These real shapes of the roller at high temperature are obtained by adding the thermal deformation to the initial shape of the roller.

For the higher taper, the final profile of the roller is convex for both strips, which contributes to maintain the strip on line. But the wider strip sees a higher crown, which is a critical situation for heat buckling. The calculation with a taper of 1,5 mm shows a roller shape almost flat for the wide product and a concave shape for the narrow one. In this case, the narrow strip might be laterally displaced or deformed.

Optimizing the roller shape consist in choosing the shape that will lower the wrinkling risk by selecting a initial shape of the roller so that its final shape for the wide products will be as flat as possible, and its final shape for narrow products is as convex as possible (or the less concave that can be done) to avoid lateral strip displacement.

So making a proposal for a criterion on the final shape of the roller is necessary in order to achieve the compromise between wrinkling and lateral displacement. That was the aim of the study of the mechanical buckling of a strip which is presented in the following paragraph.

### **MODELING STRIP BUCKLING**

A wrinkle is a plastic deformation of the strip which occurs when a buckled strip approaches a roller (figure 10). The out of plane displacement of the strip which is elastic before the roller turns out into a plastic deformation as the strips comes over the roller when critical conditions are combined.

Those conditions are related to the strip characteristics (thin thickness, wide width, flatness), the process characteristics (speed, high tensions) and the roller characteristics (shape at high temperature, friction).

As the parameters of the roller are of major importance, IRSID investigated buckling caused by the roller profile with a FEM mechanical analysis and experimental measurements in order to optimize the rollers toward the problem of wrinkling.

### **Mechanical study**

When a strip under tension is wrapped around a convex shaped roller, the center of the strip sustains a higher stress in the machine direction than the edges. This non uniform tension distribution generated on the width of the strip makes the strip buckling.

The strip buckling was studied with a finite element method (FEM) in IRSID and in the Laboratory for Physics and Mechanics of Metz (LPMM, Metz, France) [1]. The simulations are made with the FEM code ABAQUS 5.3, using a non linear incremental approach, first with a static roller, then with a rotating roller.

### **FEM static calculations [2]**

The assumptions of the static calculation are :

- the roller is tapered (figure 11a),
- the strip is elastic and centered on the roller so that only half of a strip is modeled (figure 11b),
- no  $u_y$  displacement is allowed on the center line of the strip and no radial displacement is possible on the flat part of the roller (figure 12),
- a uniform tensile stress is applied to the strip at the end of the span.

In the static model, the buckling shape before the roller and the longitudinal and transverse stresses in the strip are calculated for an increasing tension. At each step of the simulation, the contact area between the strip and the roller is calculated.

Calculations are made with a IBM 3CT computer. The strip is meshed with ABAQUS elements S4R5 (4 modes and 5 degrees of freedom per mode). In order to simulate the contact conditions between the strip and the roller, contact elements IRS4 are used.

Figure 13 shows the stresses in a 820 mm wide strip for a uniform tensile stress applied of 40 Mpa. We can see that the magnitude of the stresses in the machine direction decrease from the center of the strip to its edge where it has even a zero value. In the transverse direction, a compressive area appears in the strip just before the roller. This compressive area is responsible for the buckling of the strip.

Figure 14 shows the contact area for two levels of tension. At low tension (4 Mpa) the area of contact is small ; for a higher tension (40 Mpa), the area of contact is more important but there is still not a total contact between strip and roller. The dependence of buckling with tension is influenced by contact conditions : first buckling develops as contacts develops with increasing tension, then buckling is stabilized when the contact is total.

In the next paragraph, calculation of strip shapes are compared to measurements.

### **Experimental measurements**

Shapes of static cold strips wrapped around a profiled roller were measured on a high scale pilot line in IRSID with a three points distance measurement device, moved in front of the strip in the transverse direction at different distances of the roller.

Figure 15a shows the shape of a steel strip measured at a tension of 67 Mpa. Figure 16 shows the evolution of buckling mode of the strip at 500 mm of the roller measured for three tensions. As tension increases, there is a higher number of undulations and the undulations become narrower.

Figures 15b and 16b show a good agreement between calculated shapes and measurements.

### **Modeling a rotating roll**

The calculation runs in two steps :

- in the first step the static calculation is made for a given tension,
- in the second step, the strip travels over the roll, and the elastic buckled deformation turns into plastic deformation.

In the second step of the calculation, contact with friction is considered between the strip and the roller and the strip has an elasto-plastic behavior.

Critical tensions for buckling measured on the CRM experimental pilot line on steel at high temperature showed a good agreement for tin plate strips between measurement and calculation (table 1).

### **INDUSTRIAL APPLICATIONS**

With the models, new sets of mechanical roller profiles could be applied on three continuous lines of SOLLAC [4]. The thermal model was used to calculate for different products the roller shapes at high temperature obtained with the initial set of roller profiles. The buckling model was used to calculate critical shapes for buckling. When the roller shapes at high temperature were found to be critical, a proposal for new mechanical profiles was made. The optimization of roller mechanical profiles led to quality improvements and critical products to wrinkling were easier processed.

### **ACKNOWLEDGMENTS**

We would like to thank V.Gueydan and M.Potier-Ferry, from the Laboratory for Research in Physics and Mechanics of the University of Metz (LPMM), for calculations made on strip buckling [1]. We are also grateful to the French company for engineering Stein et Heurtey (Evry, France) and especially to MM Dubois, Song and Boyer for giving us the opportunity to compare our thermal model to theirs.

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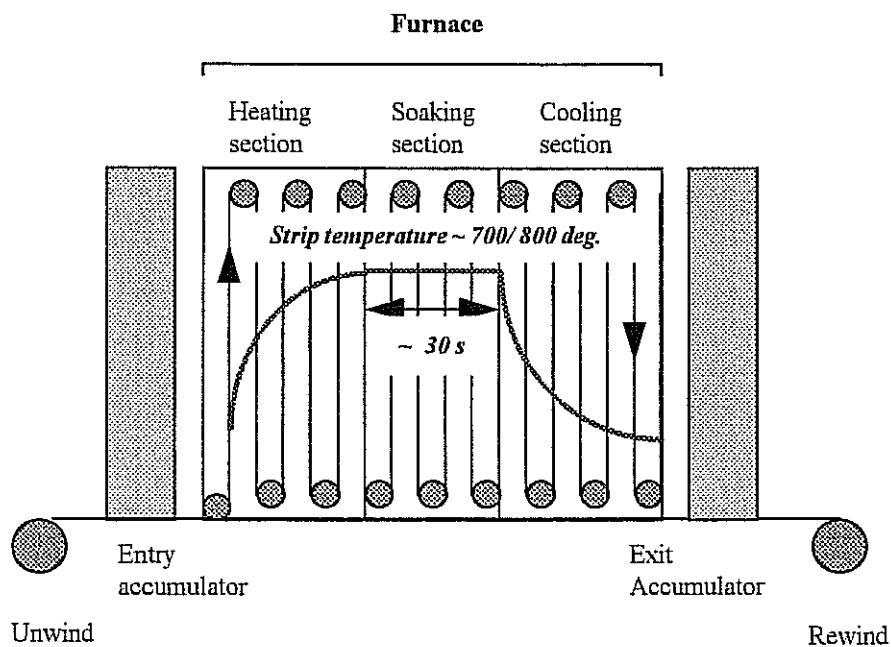


Fig. 1 Schematic view of a continuous annealing line.

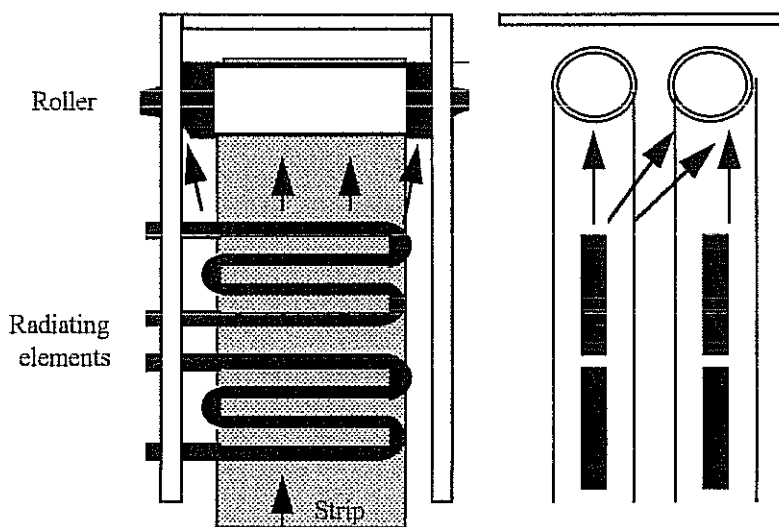


Fig. 2 The radiating elements are heating the rollers.

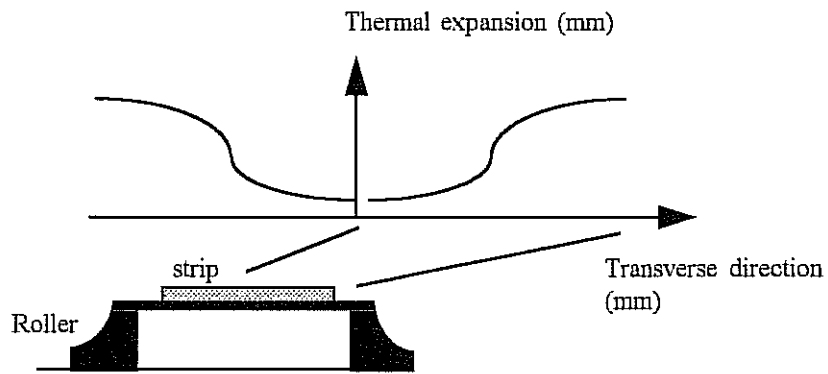


Fig . 3 Thermal expansion of the roller.

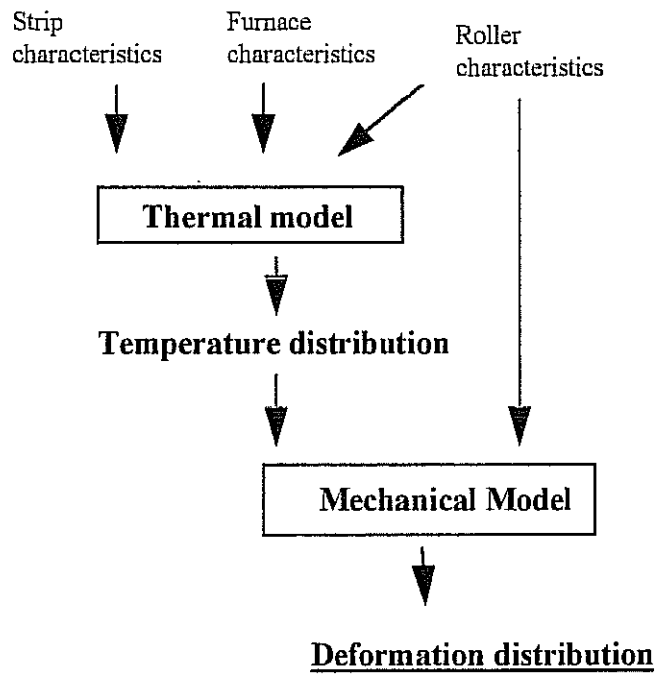


Fig. 4 Calculation of the deformation distribution on the roller.



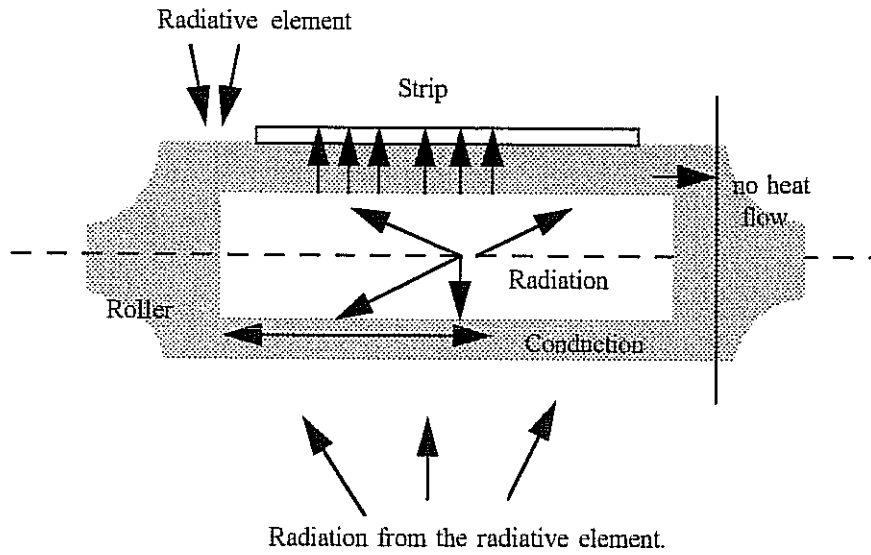


Fig. 5 Flows influencing the thermal equilibrium of the roller.

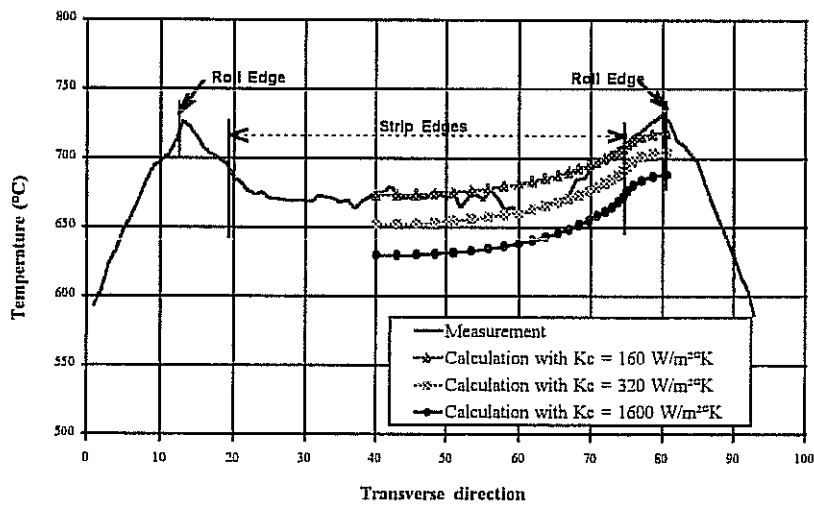


Fig. 6 Roller temperature distribution measured and calculated for 3 transfer coefficients  $K_c$  ( $t = 0.19 \text{ mm}$  ;  $w = 300 \text{ mm}$ ).

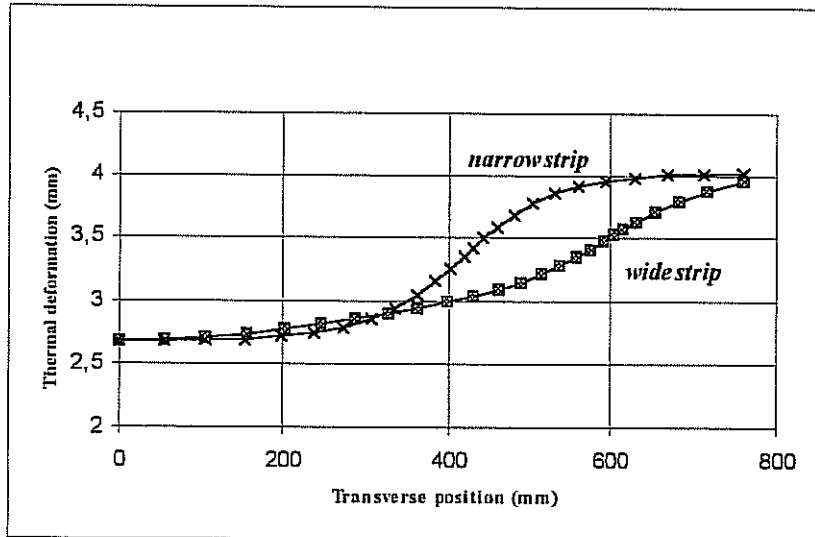


Fig. 7 Thermal deformation distribution for two strip widths  
 (narrow strip :  $w = 850$  mm,  $t = 0.25$  mm ;  
 wide strip :  $w = 1220$  mm,  $t = 0.25$  mm ).

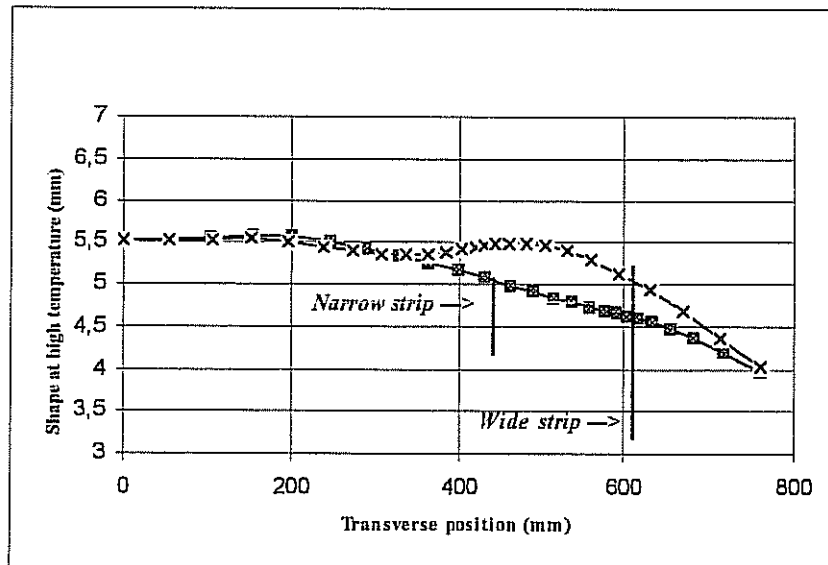


Fig. 8 Roll profile at high temperature for a taper  $\Delta h$  of 3 mm  
 (narrow strip :  $w = 850$  mm,  $t = 0.25$  mm ;  
 wide strip :  $w = 1220$  mm,  $t = 0.25$  mm ).

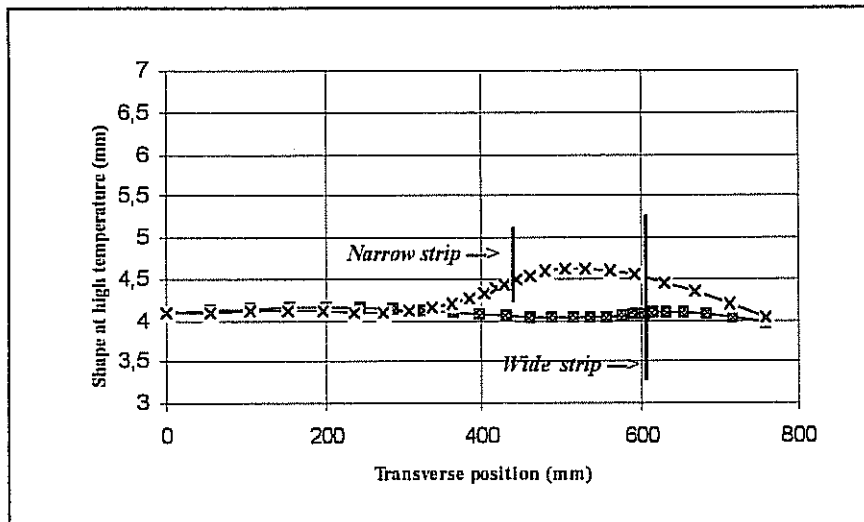


Fig. 9 Roll profile at high temperature for a taper  $\Delta h$  of 1.5 mm  
 ( $W_{fp} = 350$  mm ; narrow strip :  $w = 850$  mm,  $t = 0.25$  mm ;  
 wide strip :  $w = 1220$  mm,  $t = 0.25$  mm).

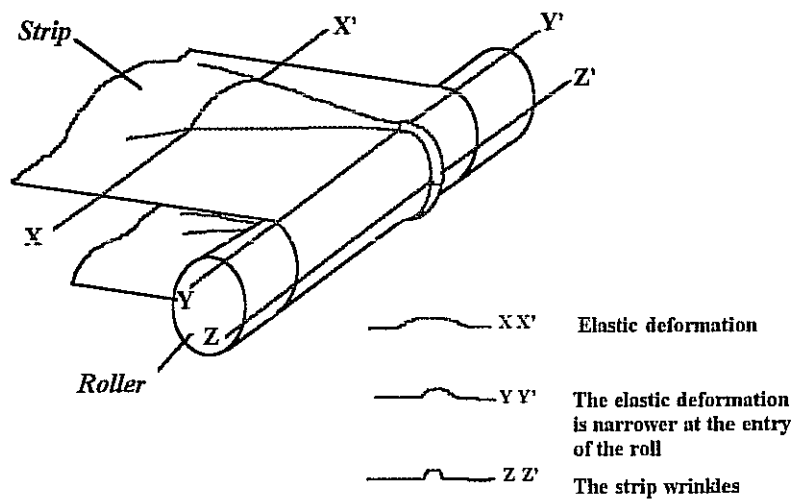


Fig.10 Strip elastic buckling and wrinkling on a roller.

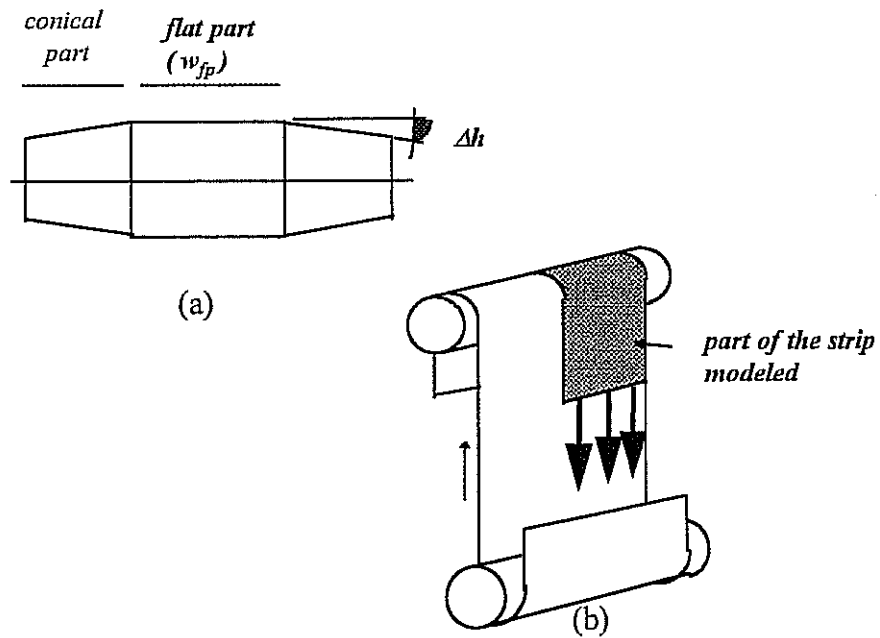


Fig.11 Geometry of the roll and part of the strip modeled.

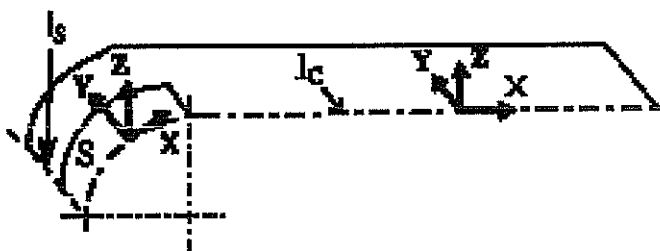


Fig.12 Boundary conditions for the FEM calculation :

- symmetry/X on  $l_c$  :  $u_y = \theta_x = 0$
- symmetry /X on  $l_s$  :  $u_x = \theta_y = 0$
- flat part of the roll (S):  $u_z = \theta_z = 0$ .

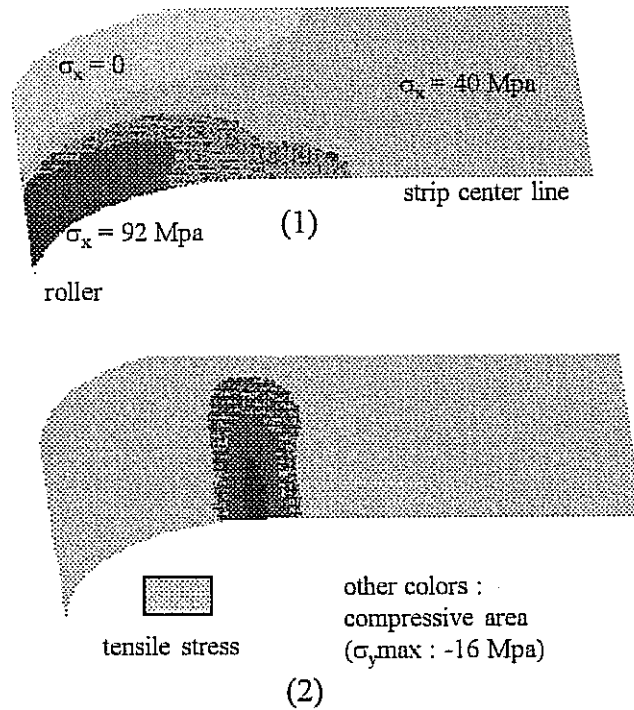


Fig. 13 Stresses in the strip  
 (1) Machine Direction  
 (2) Transverse Direction  
 ( $w = 820 \text{ mm}$ ,  $t = 0,09 \text{ mm}$ ;  $W_{fp} = 820 \text{ mm}$ ;  $\Delta h = 1 \text{ mm}$ )

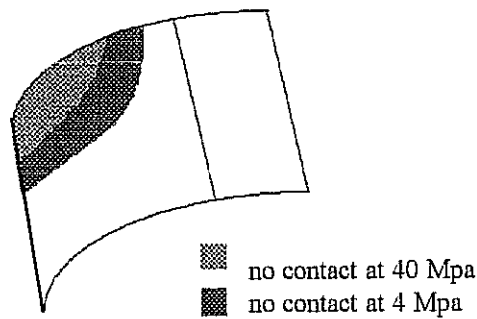


Fig. 14 Area of contact between the strip and the roll for 2 tensile stresses  
 ( $w = 820 \text{ mm}$ ,  $t = 0,09 \text{ mm}$ ;  $W_{fp} = 820 \text{ mm}$ ;  $\Delta h = 1 \text{ mm}$ ).

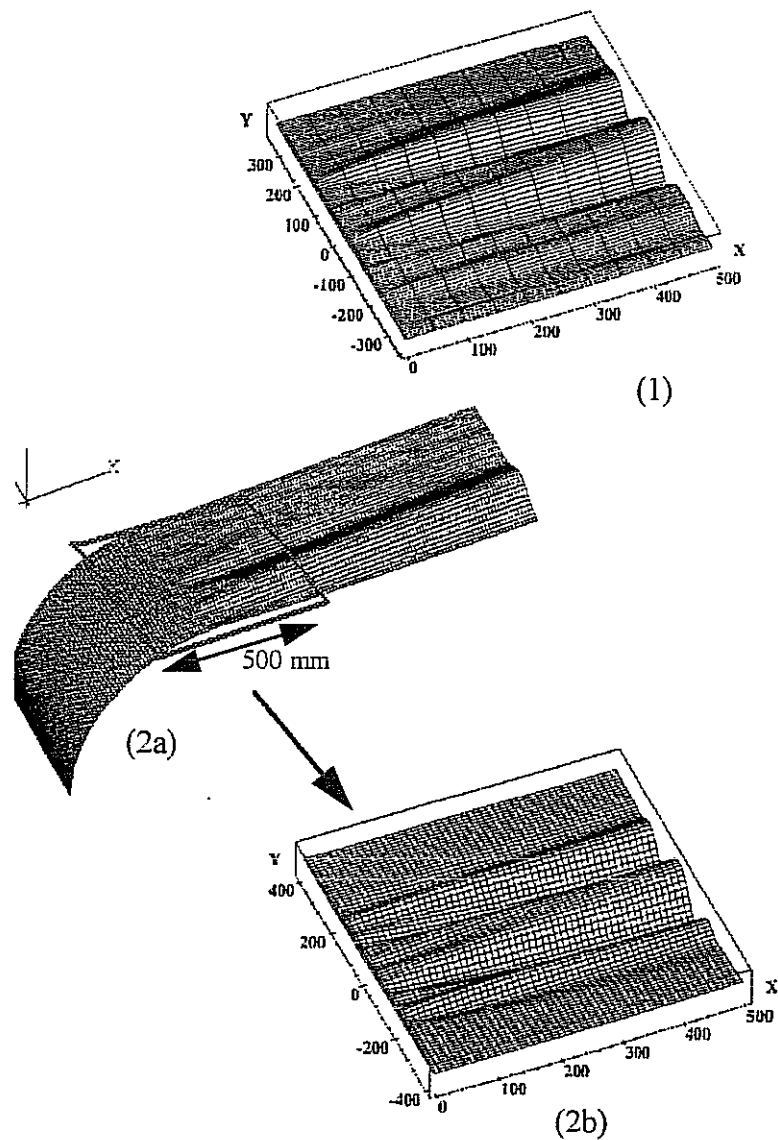


Fig.15 Shape of a steel strip before a profiled roll  
 (1) measurement for  $\sigma_x = 67$  Mpa  
 ( $w = 820$  mm,  $t = 0,09$  mm ;  $W_{fp} = 390$  mm ;  $\Delta h: 1$  mm ).  
 (2a) calculation for a length of 1000mm  
 (2b) calculation for a length of 500 mm.  
 (mesh of 8570 S4R5 shell elements and 2560 contact elements ; 45 000 degrees of freedom).

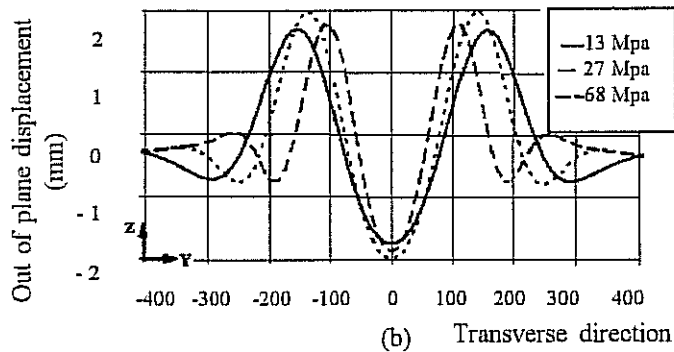
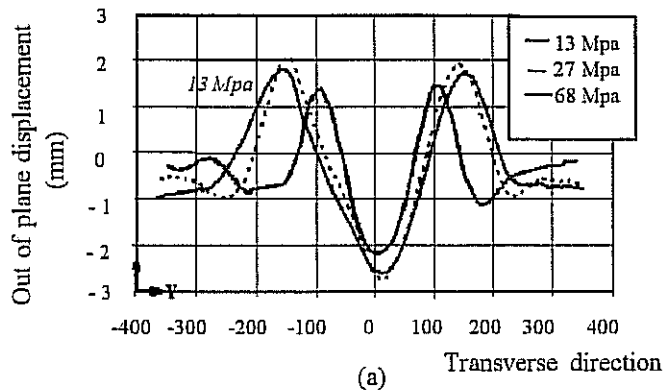


Fig.16 Shape of a steel strip at a distance of 500 mm from the profiled roll for three tensile stresses  
 (16a) measurements ( $w = 820$  mm,  $t = 0,09$  mm ;  $W_{fp} = 390$  mm ;  $\Delta h = 1$  mm).  
 (16b) calculations.

Metal	-	Steel	Aluminium
Thickness	mm	0,19	0,19
Width	mm	300	300
Temperature measured	°C	730	20
Young modulus	Mpa	130 000	70000
Yield Stress measured	Mpa	49	50
Critical tension measured	Mpa	6,5	12
Critical tension calculated	Mpa	8,5	13

Tab. 1: critical tension measured on the CRM pilot line for steel at high temperature and aluminium at room temperature (roller characteristics :  $w_r = 350$  mm ;  $w_{fp} = 100$  mm ;  $\Delta h = 1,3$  mm ;  $D = 750$  mm ;  $Ra = 6$   $\mu$ m ).

Question - Figure 15 plot of the measured deflection, how did you generate that plot?

Answer - We made a special device with 3 sensors which were measuring distance to the strip with high accuracy and made measurements. We did this with total precision of the head which was enough to make comparisons. This head was moved in the transverse direction and in the machine direction so we could describe which shape of the strip.

Question - What was the diameter or radius of the crowned rollers and how much difference in the radius did you put on them?

Answer - Depends on the line. Typically between 650 mm and 800mm. Its 650 for the line for packaging and for the automotive lines.

Question - 650 to 800 mm is pretty big.

Answer - It is big.