Stretch-reducing Mill: the effect of the factors of influence on thickened ends

C. Mapelli, L. Montelatici

The understanding of the effect of the factors of influence on the thickened ends needs to be more clearly understood, so neural network model (DALNN1_Dalmine Neural Network1), trained by a genetic algorithm (GENDAL1_Genetics Dalmine1), has been developed to compute the thickness of the ends as function of the operative parameters of the stretch-reducing mills. The forecasting of the model showed a good performance that avoids other complicated developments based on precise structural approaches that generally are really time consuming. The possibility to make the procedure automatic allows to determine the development of the thickened ends and as a consequence to minimize the discarded material of the pipe that is not in the limits imposed by the geometrical specifications. These study is about the determination of a map of rolling that can consent to understand the effect of the different operative factors and can lead the operators to a better control of the process.

Parole chiave: acciaio, laminazione, qualità

INTRODUCTION

The hot rolling of pipes finds a good quality and a high productivity system in the stretch-reducing mill. The productivity of this process can be significantly improved by the correct evaluation of the thickness of pipes during and after the rolling process. A great care has to be paid to the determination of thickness along the whole length of the pipe that should remain within the limits imposed by the geometrical specifications. The thickened ends are not eliminable, but great efforts were spent in the past to minimize the thickened ends of the rolled pipes, and at least to control this drawback.

Yamada et al. (1) attempted to develop a model for the rapid determination of the length of the thickened ends. But this model can be applied only to a little typology of pipes and it does not consider an important factor such as the total tangential logarithmic deformation. However, this study led to reliable determination of the end thickness and the length of these ends. Ricard and Bryan (2) used a statistical approach based on the factorial analysis and a multivariable regression to determine the influence of each factor and its weight, but the results don't seem to satisfy the industrial practice for the high number of test tasks that are required.

The periods of plastic deformation that characterizes such a process can be so summarized:

- perforation that leads to a rough pipe of great thickness;
- elongation that causes the simultaneous reduction of the diameter and thickness of the pipe;
- calibration which leads the rolled pipe within the required geometrical specifications.

Each period is implemented by a specific section of the strands of the mill.

The aim of the development of a new model is the suitability of its results to a wide range of products and the possibility to support the operators by an automatic computation of the thickened ends as function of the distance from the ends of the pipe. This can permit to increase the performance of the rolling plant, by the decrease of the discarded material, and to improve the coordination between two different subjects involved in the process, the steelmaking unity and the rolling one. Actually, by the use of a reliable model, the steelmaking unity could produce a billet with a right length to diminish the discarding material of the final product that is a function of the geometrical features of the pipe and the relative productive parameters of the stretch-reducing mill. The availability of some maps about the thickening of the ends of the pipes is a topic issue that can permit to make automatic the process of determination of the thickened ends.

The approach described here is based on a mathematical model that can represent the trend of the thickness at each point from the end of the pipe as a function of the geometrical features of the pipe to be produced and the consequent productive parameters applied: distance from the end, average stretch, percentage diameter reduction of each strand, inter-strand distance (distance between two successive strands of the mill), total tangential logarithmic deformation. This model is based on a neural network approach and is implemented by two cooperating software modules developed by a C++ language code (DALNN1_Dalmine Neural Network1), while the training procedure is performed by a genetic algorithm (GENDAL1_Genetics Dalmine1).

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THE STRETCH-REDUCING MILL PROCESS

The stretch-reducing mill is composed by a series of strands (up to a maximum of 30 strands) with three cylinders rotating at increasing speed and in excess with respect to the constant material flow. By this method a stretch is generated on the worked material between a strand and the successive one with a contemporary reduction of the pipe thickness; to avoid undesired slips between the worked material and the cylinder surface it needs that the longitudinal stretch strength don't exceed the friction forces. The stretch-reducing mill has a high productivity, and the exit speed can vary between 3-5m/s, so it is very suitable system to fabricate pipes of little diameters and thickness.

Each strand is rotated of $\pi/6$rad respect to the former one

and is structured to allocate three cylinders disposed at π/3rad from each other.
The stretch-reducing mill after a primary rolling plant allows to reach some aims:
- the increase of the productivity of the plant because it can treat rough pipes of a wide geometrical range;
- the variation of the final diameter without the change of the diameter of the rough pipe;
- the production of pipe of little inner diameter without expensive supplementary machining operations and avoiding the change and mantainance of a spindle;
- improve the geometrical characteristics and the surface quality of the pipes.

The thickness is governed by the modulation of the longitudinal stretch imposed by the increasing speed of the cylinders. The stretch level depends on the relative speeds between the strands.
The longitudinal stretch required to obtain the desired thickness is reached only when the pipe is under the action of all the strands. When the forward end of a pipe enters the series of strands the corrisponding stretch increases progressively up to a maximum value when the whole pipe is within the strands. So the ends on the backward end and on the forward end of the pipe are under a different stress condition which implies a different strain status respect to the region of the pipe far from the ends (fig.1).

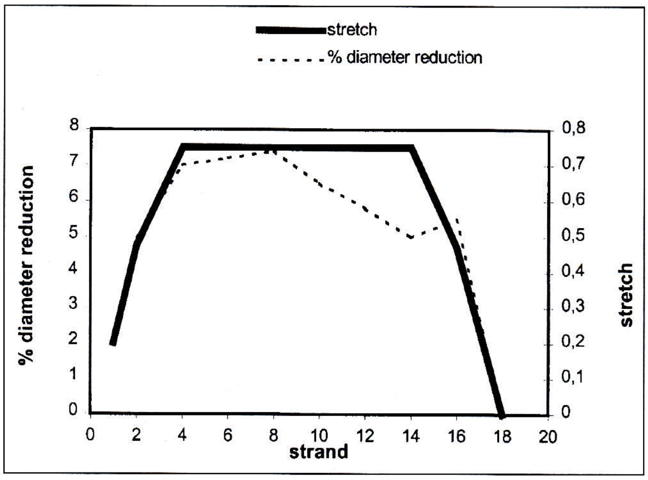

Figure 1. Example of the trend of longitudinal stretch and of the percentage diameter reduction of each strand.

Figure 1. Esempio dell'andamento dello stiro longitudinale e della riduzione percentuale di diametro di ogni gabbia.

The problems rise because the ends of the pipe are subject to a different stretch respect to the situation of the central regions (fig.2) here represented (conditions for longitudinal stretch and percentage diameter reduction acting far from the ends). This situation causes the increase of the thickness of the ends and the portions that exceed the geometrical specifications have to be cut off. The length of the thickened ends is determined by the maximum possible variations of stretch from the entrance to the exit of the single strands and this stretch can be varied only gradually. This phenomenon is influenced by the following factors (3):
- the stretch;
- the rate of diameter reduction;
- inter-strand distance;
- total logarithmic deformation (as defined in the following of this paragraph).

From the deformation theory of the material it is possible to obtain the relations linking the geometrical characteristic and the parameters involved in such a rolling process(4,5,6).
The shape modification depends on the ratio between the

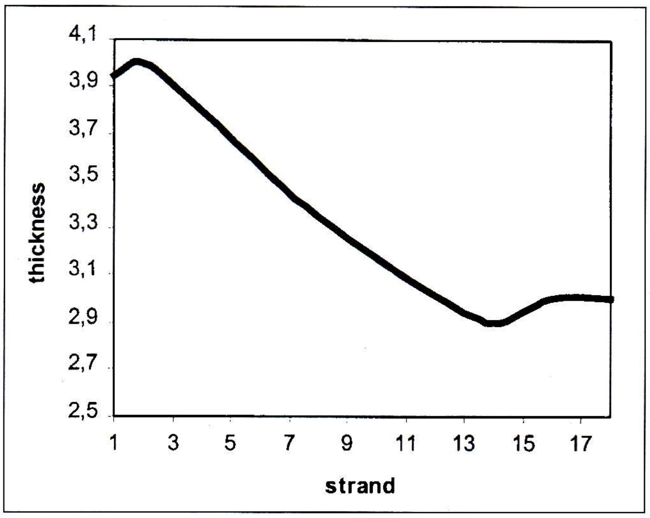

Figure 2. Example of the trend of thickness reduction in a 17 strand mill.

Figure 2. Esempio di evoluzione della riduzione di spessore in un laminatoio con 17 gabbie.

longitudinal and radial stresses.
During the hot deformation process the stresses developed are:
- σ_t tangential stress;
- σ_r radial stress, computed as the average value on the medium radius;
- σ_l longitudinal stress.

This stresses are linked by the following relations:
- $\sigma_r / \sigma_t = 1 - (R_i / X)$ Where R_i = inner radius and X = radial coordinate.
- σ_r / σ_t = Thickness / (Outer_Diameter.–Thickness) = ε Thickness radius of the pipe.
- $\sigma_l - \sigma_t = K_f$ deformation coefficient of the material that includes the plasticity behaviour of the material as expressed according to the Tresca criterion.

The tensions acting on the pipe produce a reduction of the outer diameter, a length increase and a reduction of the thickness.
When the stress condition exceeds the plasticity condition, the pipe changes its shape significantly and this modification can be summarized by these parameters:

$$\varphi_l = \ln\left(\frac{L_0}{L_1}\right)$$ total logarithmic length deformation,

$$\varphi_r = \ln\left(\frac{S_0}{S_1}\right)$$ total logarithmic thickness reduction,

$$\varphi_t = \ln\left(\frac{D_0 - S_0}{D_1 - S_1}\right)$$ total tangential logarithmic deformation.

Where L_0, L_1 are the initial and final length of the rolled pipe, respectively; S_0 and S_1 are the initial and final thickness of the pipe.
From the Hencky's Theory these can be expressed through the principal tensions:

$$\varphi_l = (\sigma_l - \sigma_{average})$$

$$\varphi_r = (\sigma_r - \sigma_{average}) \quad \text{where} \quad \sigma_{average} = \left(\frac{\sigma_l + \sigma_r + \sigma_t}{3}\right)$$

$$\varphi_t = (\sigma_t - \sigma_{average})$$

The stretch is expressed as: $X_l = \dfrac{\sigma_l}{K_f}$

and assumes value within the 0,05 and 0,85 limits.
Under a minimum value the thickness reduction does not take place while over an upper limit there is the crushing of the pipe. It is possible to express the principal deformation as function of the stretch X_l and of the ratio between the thickness of entry and that of the exit:

$$\varphi_l = [X_l * (1-\varepsilon) + (1+\varepsilon)]$$
$$\varphi_r = [2 * X_l * (\varepsilon - 1) + (1 - 2*\varepsilon)]$$
$$\varphi_t = [X_l * (1-\varepsilon) + (2-\varepsilon)].$$

The measures required to implement this method are: the outer diameter of the rough pipe, the final outer diameter, the initial and the final thickness. To determine the operative parameters the following relations are used:

$$X_{l\_average} = \frac{\frac{\varphi_r}{\varphi_t} * (2-\varepsilon_m) + (1-2\varepsilon_m)}{\frac{\varphi_r}{\varphi_t} * (1-\varepsilon_m) - 2*(\varepsilon_m - 1)}$$

where:

$$\varphi_r = \ln\left(\frac{S_0}{S_1}\right), \quad \varphi_t = \ln\left(\frac{D_0 - S_0}{D_1 - S_1}\right),$$

$$\varepsilon_m = 0{,}5 * \left[\frac{S_0}{D_0 - S_0} + \frac{S_1}{D_1 - S_1}\right]$$

The value of the maximum stretch is determined by :

$$\gamma_{l\_tot} * X_{l\_average} = \sum_{strand=1}^{n} \gamma_{l\_strand} * X_{l\_strand}$$

Where γ_{l_tot}, γ_{l_strand}, X_{l_strand} and n are the total tangential logarithmic deformation, the total tangential logarithmic deformation of the l_strand, the stretch of the l_strand and the number of the strands, respectively. The ends of the pipe are subject only to the action of a part of the strands. The average longitudinal stretch can be expressed as a function.
The outer diameters of entrance and exit from the single strand (d_{aq0} and d_{aq1}) are needed to compute X_{l_strand}. The tangential deformation φ_t and the average value of the thickness ratio (ε_m) can be determined by the knowledge of the entrance thickness S_{q1} after the strand of interest. Because the value of this thickness is not known till now, as first approximation it is assumed as that of entrance, so $S_{q1}=S_{q0}$. By suitable simplification the following equations are obtained (provided $^{(*)}$ and $_{(q)}$ indicate a measure related to a single strand q):

$$\varphi^*_{tq} = \ln\frac{d_{aq0} - S_{q0}}{d_{aq1} - S_{q0}}$$

$$\varepsilon^*_q = 0{,}5 * \left[\frac{S_{q0}}{d_{aq0} - S_{q0}} + \frac{S_{q0}}{d_{aq1} - S_{q0}}\right]$$

$$\frac{\varphi^*_{rq}}{\varphi^*_{tq}} = \frac{2 * X_{lq} * (\varepsilon^*_q - 1) + 1 - 2*\varepsilon^*_q}{X_{lq} * (1 - 2*\varepsilon^*_q) - (2 - \varepsilon^*_q)}$$

Through these relations it is possible to write:

$$\varphi^*_{rq} = \ln\frac{S_{q0}}{S_{q1}}.$$

If the ratio between the entrance and exit thickness is near to unity it is possible to approximate:

$$S^*_{q1} = S_{q0}(1 - \varphi^*_{rq})$$

By an iterative procedure the value of found is inserted in the former equation and so on until the value is not stable.

THE NEURAL NETWORKS AND THE THICKENING MAPS

The former approach represents a correct physical interpretation of the material behaviour during the stretch-reducing mill process. But it cannot be used to obtain the indication about the thickened ends with the precision industrially required to implement en efficient process. An innovative approach that involves the interaction among the different significant parameters of the process is needed, so that the operators can apply a rapid and automatic procedure to use a first billet with the correct geometrical parameters and adjust all the productive parameters to implement an efficient process, decreasing the discarding materials. The neural networks approach seems to satisfy these needs.
Two main types of models can be used to understand and describe a technological process: physical models and statistical models. The neural networks belong to the second category, but their performance is greater than that of a linear regression with which most scientists are familiar, because the neural networks show at least three strong aspects that differentiate them from the classical linear or pseudo-linear regressions (7,8):

- the users are not constrained to choose a previous hypothesis about the relationship among the factors;
- the neural networks can describe very well non-linear relationships among the inputs factor and between these ones and the outputs.

A neural networks model is composed of different layer of nodes. Generally, the first layer of nodes is the input layer, while the last one is the output layer. These extreme layers are linked by a network formed by other layers, named hidden layers, which are linked in a complex network that permits the information transfer from a node to the other ones (fig.3). The input data are multiplied by weights which characterize every single linkage between the nodes (w_i) and the sum of all the product becomes the argument of a non-linear function, that in the case of the present model is the hyperbolic tangent (hidden function):

$$h = \tanh\left(\sum_i w_j^{(1)} x_j + k\right)$$

where k is a constant value, named bias value, and x_j is the input value coming from the former layer.
The weights of the successive layer eventually present are indicated as $w^{(n)}$.

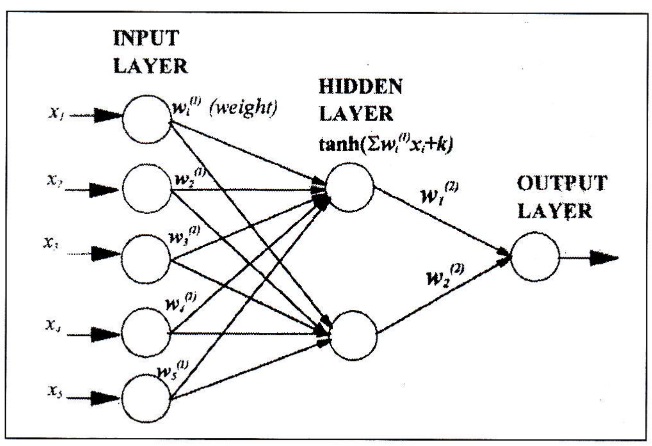

Figure 3. Structure of the neural network with three layers.

Figure 3. Schema di rete neurale a tre strati.

The core of the method consists in the definition of the weights that link the different node and the procedure for this definition is the training of the neural networks, that needs some experimental tasks. The weights that define the interactions between the factors are adjusted on the basis of the experimental tasks, in which the value of the chosen factors of influence (input factors) were known and the output values were measured. Through a drawback propagating algorithm the networks is trained by the computation of the weights. In this case a genetic algorithm (9) of back propagation was developed (and named GENDAL1) based on previous model proposed by Cormier and Raghavan(10).
The correct number of nodes and layers is fundamental for the stabilization of the weights of the networks. The neural networks is composed of three layers (one input layer, one hidden layer and one output layer) and the number of the nodes are defined by an empirical procedure (11), provided that there are five input nodes (average longitudinal stretch, average percentage reduction of external diameter, distance from the ends, inter-strand distance, total logarithmic diameter deformation). The set of the weights are stable even after the training implemented by a little amount of pipes. An experimental procedure was developed on two different strectch-reducing mills belonging to DST Dalmine (12) to validate the model, and from the results obtained it is possible to draw the thickening maps describing the thickening trend of the ends.
DALNN1 can forecast the distance at which the thickened ends reach the nominal value of the geometrical specifications and the corresponding maximum and minimum thickness of the pipe.
But it is also possible to draw some maps representing the thickening trend of the ends on the basis of a simultaneous change of the percentage diameter reduction per strand and the total tangential logarithmic deformation needed for obtaining the pipes with the desired geometrical specifications (fig.4, fig.5).

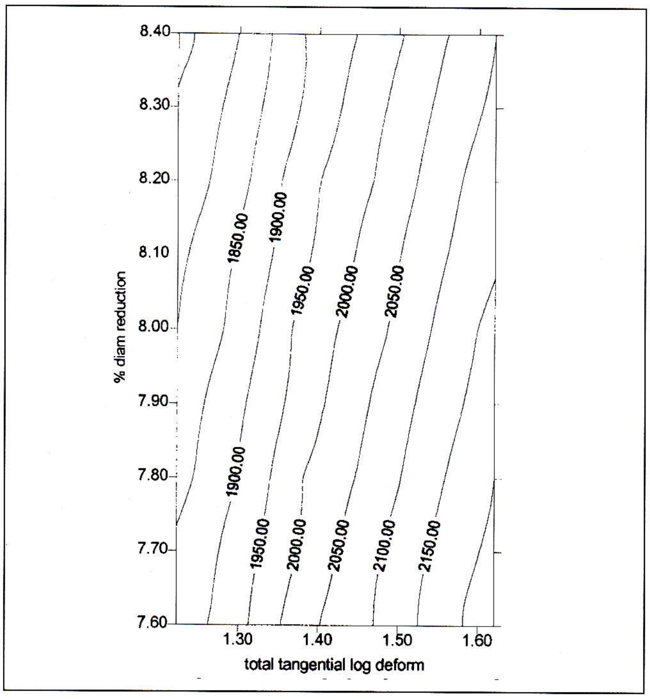

Fig.4 Length of the forward ends to the nominal thickness as function of percentage diameter reduction and total tangential logarithmic deformation.

Fig.4 Distanza dalle estremità di testa sino al raggiungimento dello spessore nominale in funzione della deformazione tangenziale totale logaritmica e della riduzione percentuale di diametro

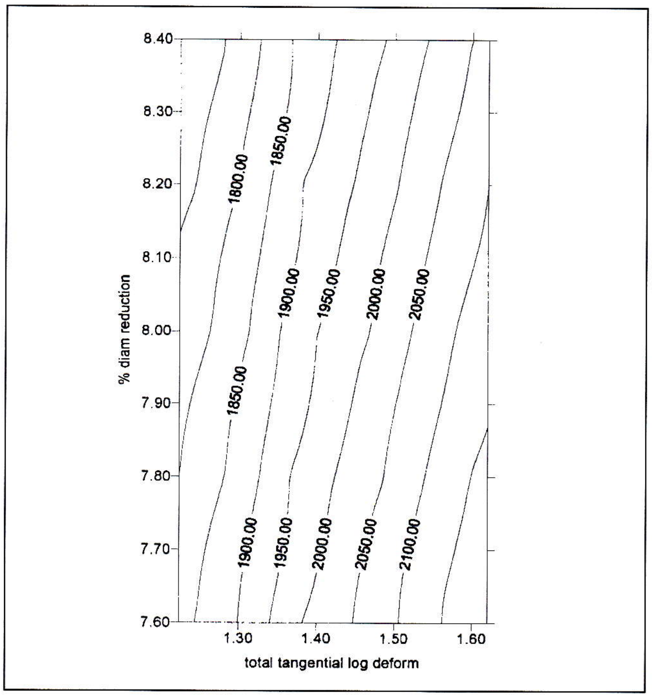

Fig.5 Length of the backward ends to the nominal thickness as function of percentage diameter reduction and total tangential logarithmic deformation.

Fig.5 Distanza dalle estremità di coda sino al raggiungimento dello spessore nominale in funzione della deformazione tangenziale totale logaritmica e della riduzione percentuale di diametro

It is possible to evaluate the non-linear behaviour and the difference between the forward side results and those corresponding to the backward side (these last are slightly lower). These two examples of rolling maps are computed through the interpolation of the data coming from five different pipes produced starting from the same rough pipe with an outer diameter of 98mm. The final outer diameter varies as function of the pipe: 22mm, 25mm, 27mm, 29mm, 31mm; while the thickness is reduced from 4.5mm to 3.5mm for all the pipes. The production of each pipe is supposed to be performed by five different tasks featured by five different percentage reduction of the diameter: 7.6%, 7.8%, 8%, 8.2%, 8.4%. The average longitudinal stretch is related and computed according to this geometrical specifications(1).
This methods appears suitable and rapid to help in the setting of the operative parameters to make efficient the rolling process by the knowledge of the length where to cut the pipe.

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(1)

$$X_{l\_average} = \frac{\frac{\varphi_r}{\varphi_t} * (2 - \varepsilon_m) + (1 - 2\varepsilon_m)}{\frac{\varphi_r}{\varphi_t} * (1 - \varepsilon_m) - 2 * (\varepsilon_m - 1)}$$

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ABSTRACT

STRETCH-REDUCING MILL: THE EFFECT OF THE FACTORS OF INFLUENCE ON THICKENED ENDS

La produzione di tubi al laminatoio stiratore-riduttore costituisce uno dei metodi a più alta produttività, infatti consente di ottenere una vasta gamma di tubi caratterizzati da differenti diametro e spessore a partire da un medesimo sbozzato.

D'altro canto, la sua efficienza è minata da alcuni inconvenienti quali l'ispessimento delle estremità di testa e di coda del tubo, che non sono soggette alla tensione di regime, ma ad una tensione inferiore. La tensione longitudinale è infatti generata dal progressivo aumento delle velocità relative di rotazione dei cilindri che si susseguono nelle gabbie del laminatoio, ma i tratti finali di testa e di coda non avvertono la medesima tensione che si instaura sui tratti a regime.

Un consistente aumento di efficienza e di produttività può essere ottenuto attraverso i processi di crop and control che si basano su una variazione tra le differenze delle velocità dei cilindri rispetto alla condizione di regime durante la laminazione dei tratti di testa di coda. Oltre a queste intervento è già possibile conseguire forti aumenti di efficienza attraverso la determinazione precisa dall'andamento dell'ispessimento delle estremità in base ai parametri operativi scelti per la laminazione.

Dalla letteratura si conoscono i parametri di influenza che maggiormente condizionano questo fenomeno: lo stiro longitudinale medio, la riduzione percentuale di diametro per gabbia, lo spazio intergabbia (o interasse tra le gabbie), la deformazione tangenziale logaritmica totale

$$\varphi_t = \ln\left(\frac{D_0 - S_0}{D_1 - S_1}\right).$$

Risoluzioni precise che cercassero di determinare l'andamento dell'ispessimento sulla base di approcci meccanico-strutturali precisi, richiederebbero un elevato dispendio delle risorse di calcolo in termini di tempo, a questo si aggiunga che alcuni tentativi di questo tipo non sono risultati abbastanza precisi per l'applicazione a livello industriale.

L'approccio qui presentato si fonda sulle reti neurali. Una rete neurale è stata sviluppata dagli autori (DALNN1_ Dalmine Neural Network 1) (fig.3) e si avvale di un software di apprendimento basato sui principi degli algoritmi genetici (GENDAL1_Genetics Dalmine 1), che è già stato validato ed è in grado di fornire tutti i vantaggi propri di questi sistemi di calcolo, quali il trattamento dei fenomeni non lineari senza che in fase di elaborazione si sia costretti a supporre una relazione predefinita fra il parametro di interesse ed i fattori d'influenza, nonché il progressivo aumento del carattere predittivo di questo approccio all'aumentare dei dati sperimentali, su cui la rete neurale viene addestrata. Una delle possibilità di utilizzo della rete è quella di determinare e sviluppare delle mappe di laminazione che rendano conto della lunghezza delle estremità ispessite, ossia della distanza dal bordo del tubo a cui lo spessore raggiunge il valore nominale previsto dalle specifiche oppure il valore massimo ed il minimo consentiti dalle tolleranze (fig.4, fig.5). In questo caso si sono estratte due mappe di laminazione per la testa e per la coda di tubi laminati con differente deformazione tangenziale logaritmica totale e la riduzione percentuale di diametro per gabbia, attraverso l'interpolazione di dati ottenuti per tubi con varie caratteristiche geometriche prodotte a partire da un medesimo tubo con diametro esterno di 98mm e spessore di 4.5mm.