Int J Adv Manuf Technol (2005) 26: 733–740
DOI 10.1007/s00170-003-2055-6

ORIGINAL ARTICLE

M. Strano

Automatic tooling design for rotary draw bending of tubes

Received: 8 October 2003 / Accepted: 4 December 2003 / Published online: 6 July 2005

Abstract Cold rotary draw bending of tubes is a CNC metal forming process widely used in industry. When planning a new process, trial and error is often required in order to calculate the proper overbending and to avoid wrinkling, excessive thinning and flattening. Process design is a critical, difficult, experience-based activity, that requires the selection of several variables.

In this paper, a comprehensive, computer-based methodology, called Tube ProDes, is proposed for process design of the rotary draw bending of tubes. The approach can be described as follows. First, numerical calculations are carried out in order to compensate for springback, to evaluate the severity of the bend (i.e. the risk of the occurrence of defects), and to assess the sensitivity of the process to a change in the material properties. Then, the tooling setup is completely designed by fuzzy logic, using the tube material properties, the geometrical data of the bend and the variables previously calculated as input.

Keywords Defect indicator · Fuzzy logic · Metal tubes process design · Rotary draw bending

1 Introduction

The minimum tool requirements for the rotary draw bending of tubes are (Fig. 1) the bend die, the clamp die and the pressure die. When, due to the tube geometry, bending is more difficult, the use of a mandrel and a wiper die might be necessary. Especially when bending long tubes, subsequently assembled into complex parts, trial and error is often required for calculating overbending and to reduce or eliminate the risk of defects (wrinkling, excessive thinning and flattening as seen in Fig. 2). Therefore, process planning is a critical and experience-based activity, that requires the selection of several variables. A comprehensive process design system has been developed by the Università di Cassino, and it is able to automatically perform process design.

M. Strano
Università degli Studi di Cassino,
Dipartimento di Ingegneria Industriale,
Cassino (FR), Italy
E-mail: m.strano@unicas.it
Tel.: +39-0776-2993719

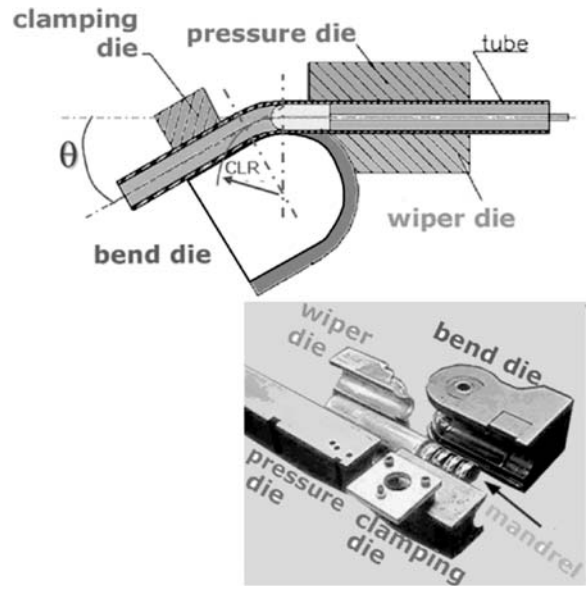

Fig. 1. Complete tooling setup for rotary draw bending

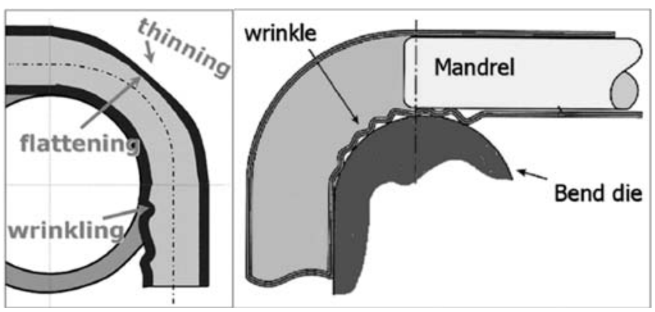

Fig. 2. Main possible defects during tube bending (thinning, flattening, wrinkling)

It is worth mentioning that the proposed system is aimed at automatically providing “good” solutions from a technological standpoint, where the word good means “similar to a decision taken by a skilled process designer”. In other words, the goal of the proposed method is not to reduce the occurrence of defects, which might be thought as a by-product of the approach, but to facilitate and accelerate process design.

The sequence of design choices taken by the proposed methodology (Tube ProDes) is described as follows.

In the first place, according to the desired centreline bending radius CLR (mm) and bending angle θ (mm) (see Fig. 1), the operating bending angle θ_0 and the required feeding length Fl must be selected, by taking into account springback effects and by considering the risk of wrinkling, thinning and flattening. Once the process parameters θ_0 and Fl have been selected, the tooling must be designed. Many variables are univocally and automatically dependent on the tube outer diameter OD and on the actual bend radius R_0 (i.e. compensated for springback), whose selection is neither critical nor difficult. However, there is another set of tooling design variables, whose value may strongly influence the quality of the bent tube. The length of the clamping die L_{cd} and the type T_{pd} and length L_{pd} of pressure die (see Figs. 3 and 4) have to be chosen. T_{pd} is a linguistic variable, since the pressure die can be “stationary”, “roller”, “friction follower”, “pressure follower” or “with boosted tube”. In the present context, a linguistic variable is meant as a variable obtained as an output of the fuzzy decision system, which does not undergo de-fuzzification.

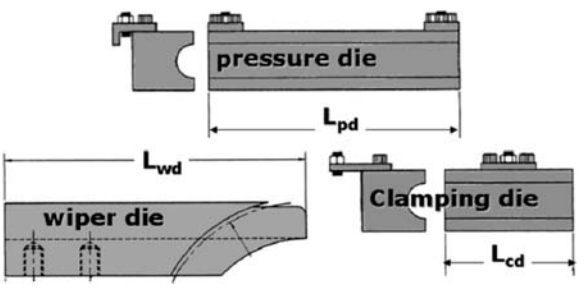

Fig. 3. Main design parameters for pressure, wiper and clamping dies

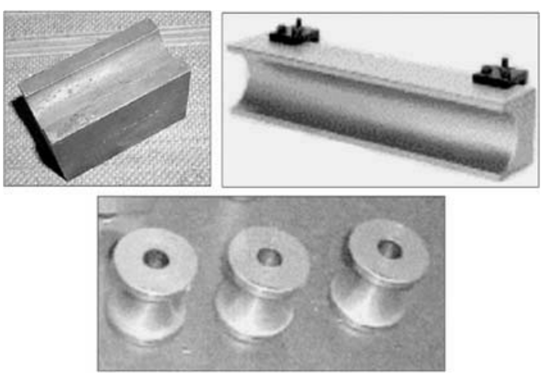

Fig. 4. Some types of pressure dies, stationary (*top left*), roller (*bottom*), follower (*top right*)

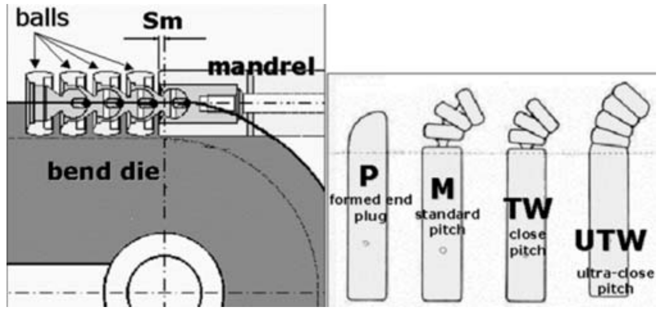

Fig. 5. Main design parameters for mandrels (*left*) and four different configurations for mandrels (*right*)

The basic tooling setup is now designed. For severe bends, using a mandrel and/or a wiper die might be necessary.

Mandrels are generally used to prevent wrinkling and flattening. The type of mandrel, if required, has to be chosen (it can be one of the four kinds depicted in Fig. 5). The related design variable T_m is therefore of a linguistic nature and can take one of the values “N” for no mandrel, “P” for plug mandrel, “M” for a standard pitch mandrel, etc. If a mandrel is used, the tangent setting S_m (mm) must be estimated and, in case of an M, TW or UTW kind of mandrel, the number of mandrel balls B_m must be decided.

Finally, the use of a wiper die must be considered, especially if wrinkling should be prevented. The related design variable W_d is Boolean, assuming the value “0” if no wiper die must be used and “1” if the wiper the should be used. When $W_d = 1$ the length L_{wd} (mm) and tangent setting S_{wd} (mm) of the wiper die have to be calculated (see Fig. 3).

2 State of the art for computer based process design of rotary draw bending of tubes

The topics found in the scientific literature, concerning tube bending process design, are usually focused on the prediction of one or more of the plastic bending phenomena (springback, thinning, wrinkling and flattening) [1–8]. One of the more recent and convincing studies on the prediction of bending mechanics can be found in [9]. Some of the mentioned papers have been used as an aid in the development of Tube ProDes.

When looking for systematic design guidelines to the selection of tooling, the literature is a little less extensive [10–12]. In [13], the authors describe a computer package for automatic calculation of the springback correction in multiaxis tube bending and for computer aided generation of the NC code for a bending machine.

Very little published information is available concerning computer based comprehensive methodologies for complete process design. Some examples are described as follows.

In [14] a knowledge-based system has been developed to aid the design of tube bending processes. Object-oriented programming techniques and goal-driven search mechanisms, featured by an interactive graphic user interface, have been applied in the development of the proposed knowledge-based system. However, the system is able to propose suggestions for finding out the causes of defects, but no examples of application are given, and as a consequence, the actual outcome is not very clearly stated.

In [15] a comprehensive software tool is described, based on a combination of numerical calculation and artificial intelligence. The approach is very similar to the one implemented in Tube ProDes, but is specialised for a special machine for the post-fabricating of miniature metal tubular components.

From a commercial standpoint, a few software packages are available and able to assist the designer in simple calculations (e.g. *AutoTube*, *VRbending*, etc.), but are very far from being a comprehensive approach for a complete design of the rotary draw tube bending process. To the author's knowledge, some manufacturers of bending machines do have developed software tools for tooling design, but their approach is extremely proprietary and no information has been published.

3 Description of the methodology

As already shown in Sect. 1, the amount of decision variables involved in process design are large, and the possible interactions between the different parameters are significant. For these reasons, process planning is a critical, difficult, lengthy and experience-based activity.

The proposed approach to process design can be decomposed into the following steps. First, a proper value for the overbending coefficient is selected (Sect. 3.1). Then, the feasibility of the specified bend is assessed, i.e. the thinning risk Risk_{thin}, the flattening risk Risk_{fl} and the wrinkling risk Risk_{wr} are estimated. The sensitivity of each risk to the tube material properties can also be known, where useful (Sect. 3.2). Finally, a correct tooling setup is designed, in order to reduce the risk of defects and to ensure the specified geometrical tolerances with a satisfactory process capability, mainly thanks to a fuzzy logic system (Sect. 3.3).

3.1 Calculation of overbending parameters

The first design issue is to determine the overbending coefficient for springback compensation, which can be defined as the ratio R_0/CLR, between the actual bend radius R_0 and the desired centreline radius CLR.

It is well known that [4] the springback ratio R_0/CLR, is calculated as:

$$\frac{R_0}{CLR} = 1 - \frac{M \cdot R_0}{E \cdot I_0}, \tag{1}$$

where E is the elastic modulus, M is the bending moment and I_0 is the moment of inertia. The method for calculating M has been originally developed and can be found in [16].

After bending, the geometric centroid axis arc length (CLR$*\theta$) is larger than the actual neutral axis length L [11], that can be calculated thanks to the following equation:

$$L = \left(CLR - 0.172 \cdot \frac{OD}{CLR}\right) \cdot \theta, \tag{2}$$

where OD is the tube outer diameter and L is the feed preparation length that would be used in the case of no overbending. If the overbending ratio is considered, the required feeding length Fl must be larger and could be estimated as:

$$Fl = \frac{L \cdot CLR}{R_0}. \tag{3}$$

Knowing the overbended feeding length Fl and the springback ratio, the overbended (increased) bending angle θ_0 can be calculated as:

$$\theta_0 = \frac{Fl}{(R_0 - 0.172 \cdot ODR_0)}. \tag{4}$$

3.2 Calculation of the risk of defects and their sensitivity to the material properties

When bending takes place, the outer wall of the bend gets inevitably thinner. If thinning is excessive, the tube may fracture. When a minimal tooling setup is used (bend die, clamp die and pressure die), a plain strain assumption can be done, and the tube axial strain ε_{ax} is equal, with the opposite sign, to the radial thinning strain $\varepsilon_{th} = -\varepsilon_{ax}$. The maximum axial strain in the tube during bending is equal to:

$$\varepsilon_{ax} = \ln\left(1 + \frac{OD}{2 \cdot R_0}\right). \tag{5}$$

A minimum bend radius MBR_{thin} can be defined as the minimum admissible R_0, before excessive thinning occurs, i.e. before ε_{ax} becomes equal to ε_{max}, the maximum admissible axial strain. For instance, ε_{max} can be calculated by an empirical FLD model, such as the ones found in [17]. Thus, MBR_{thin} can be expressed as in Eq. 6.

$$MBR_{thin} = \frac{1}{2}\frac{OD}{e^{\varepsilon_{\max}} - 1} \tag{6}$$

If comparing the actual bend radius R_0 with the minimum admissible bend radius MBR_{thin}, one can get an indication of the risk of excessive thinning. A quantitative indicator of the risk of thinning is therefore given by the following equation:

$$Risk_{thin} = MBR_{thin}/R_0 - 1. \tag{7}$$

Fracture may occur when $\mathrm{Risk}_{thin} > 0$, and the greater Risk_{thin} is, the more likely is a fracture.

Analogously, the risk of wrinkling when a minimal and standard tooling setup is used (bend die, clamp die and pressure die) can be indicated by $\mathrm{Risk}_{wrink} = \mathrm{MBR}_{wrink}/\mathrm{R}_0 - 1$. The value of the minimum bending radius MBR_{wrink}, when the risk for wrinkling is considered, can be calculated as:

$$MBR_{wrink} = OD\left(k_1 + k_2\frac{OD}{t}\right). \tag{8}$$

If assuming the isotropic flow stress law $\sigma = K\,(\varepsilon_0 + \overline{\varepsilon})^n$, where the initial plastic flow stress is $\sigma_0 = K\varepsilon_0^n$, the empirical constants k_1 and k_2 in Eq. 8 are:

$$\begin{cases} k_1 = 0.7208 \cdot (n-\varepsilon_0)^n - 0.4514 \\ k_2 = 0.1294 \cdot \ln\left(\frac{1+\sigma_0}{K}\right) + 0.876 \end{cases} . \tag{9}$$

Equation 9 has been developed by elaborating several empirical and theoretical formulas found in the literature (e.g. [7]), and by testing them with bending experiments, both newly executed and found in the literature.

The risk of flattening when a minimal standard tooling setup is used (bend die, clamp die and pressure die) can be connected to the indicator $\text{Risk}_{flat} = \text{MBR}_{flat}/\text{R}_0 - 1$. The value of the minimum bending radius MBR_{flat}, when the risk of flattening is considered, can be calculated as follows.

$$MBR_{flat} = \left[\frac{(\varepsilon_0 + n)^{\cdot n}}{18 \cdot \delta}\right]^4 \frac{OD^6}{t}, \tag{10}$$

where δ is the maximum admissible reduction in the tube diameter due to ovalization. Equation 10 has been experimentally determined, thanks to a large number of experimental tests on different kinds of steel tubes.

For each of the mentioned defect indicators Risk_i, three possible cases are given.

When all defect indicators are $\text{Risk}_i \ll 0$ (say < -0.5), the probability of a defect occurrence is very low, regardless of how accurate the tooling design is and of variations in the incoming material properties. The required tooling is usually simple and inexpensive.

When any of the risk variables is $\text{Risk}_i \gg 0$ (say >0.5), the probability of a defect occurrence is very high, and a feasible design solution, if any, can be found only after a careful design of the tooling. If a feasible solution is found, the economical convenience of the production must be evaluated.

When no Risk_i is $\gg 0$, but any of the defect indicator variables is $\text{Risk}_i \approx 0$ (say, $-0.5 < \text{Risk}_i < 0.5$), there is still some probability of a defect occurrence. Therefore, a careful tooling design is necessary. Besides, the quality of the bends could be strongly affected by a variation in the mechanical properties of the incoming tubes. In this case, a sensitivity analysis is required in respect of a change in the material properties. The sensitivity of the process to a change in the material properties j, with respect to the defect i, can be obtained as:

$$\Delta j\_i = \frac{|Risk_i|}{\partial Risk_i / \partial j} \cdot \frac{1}{j}. \tag{11}$$

As an example, the sensitivity to a change in the strain hardening exponent n, with respect to the wrinkling risk is given by the following ratio:

$$\Delta n\_wrink = \frac{|Risk_{wrink}|}{\partial Risk_{wrink}/\partial n} \cdot \frac{1}{n} = \\ = \frac{1250 \cdot R_0 \cdot t \cdot |Risk_{wrink}|}{901 \cdot OD^2\,(n-\varepsilon_0)^n \left[\ln(n-\varepsilon_0) + \frac{n}{n-\varepsilon_0}\right]} \cdot \frac{1}{n}\,. \tag{12}$$

The value of Δn_wrink gives an indication of how large the reduction of the n-value must be, before a bending process with a small negative Risk_{wrink} becomes a positive Risk_{wrink} (or how large the increase of the n-value must be, before a process with a small positive Risk_{wrink} becomes a negative Risk_{wrink}).

3.3 Design of the tooling setup

After the overbended angle θ_0 and the defect risks Risk_i have been calculated, the tooling setup must be completely designed, i.e. all variables previously listed must be selected: T_m, type of mandrel; B_m, number of mandrel balls; S_m, mandrel tangent setting; W_d, use of a wiper die; L_{wd}, length of wiper die; S_{wd}, tangent setting of wiper die; L_{cd}, length of clamping die; T_{pd}, type of pressure die and L_{pd}, length of pressure die. Several of these variables are not of a numerical nature, i.e. they are either Boolean or categorical. Furthermore, most of the design activities are not based on equations or mathematical models, but rather on decisions tables, rules of experience and design guidelines provided by the manufacturers of bending machines. For these reasons, most decisions for tooling design are taken by a fuzzy logic design system, interfaced to Tube ProDes, and developed thanks to a commercial software development tool (fuzzyTECH).

In the following, the tooling design methodology is described.

3.3.1 Input variables of the fuzzy design system

The fuzzy design system is based on nine input variables (see Table 1). Some of them are independent geometrical variables: the centreline radius CLR, the tube outer diameter OD and the wall thickness t. Some are calculated geometrical variables, such as the degree of bend DoB = CLR/OD, the wall factor WF = OD/t and the average bending angle, calculated as the average of all angles θ_i to be bent during one operation:

$$teta\_avg = \sum_{i=1}^{N_i} \frac{\theta_i}{N_i}. \tag{13}$$

Finally, the three risk indicators (Risk_{thin}, Risk_{wrink} and Risk_{flat}) described in Sect. 3.2 are used as input of the fuzzy system.

Table 1. Input variables of the fuzzy design system

INPUT		
Variable		Unit
Centre line radius	CLR	mm
Degree of bend	DoB	–
Outer diameter	OD	mm
Flattening risk	Risk_{flat}	–
Thinning risk	Risk_{thin}	–
Wrinkling risk	Risk_{wrink}	–
Wall thickness	t	mm
Average bending angle	teta_avg	degree
Wall factor	WF	–

As well as many other developments of the present work, the membership functions of the fuzzy input have been deduced by a combination of specially designed experiments, by a thorough and extensive study of the technical literature, and thanks to suggestions by process engineers. As an example, the membership functions for the input variable CLR are shown in Fig. 6.

3.3.2 Output variables and rules of the fuzzy design system

Seven out of nine tooling output design variables (T_m, B_m, S_m, W_d, L_{wd}, L_{cd} and T_{pd}) are selected by fuzzy logic, and are listed in Table 2. The two remaining variables (S_{wd}, L_{pd}) are calculated within Tube ProDes.

The fuzzy design system is then built onto about 90 membership functions, six main rule blocks, containing about 360 IF-THEN rules. Each rule block confines all rules for the same context. A context is defined by the same input and output variables of the rules. The rules implemented in the fuzzy decision model have been built by re-processing the extensive raw information material provided by the available technical literature, specially designed original experiments, suggestions by experienced process engineers and machine manufacturers' decision tables. All this information and data, coming from different sources, has been compared, combined and transformed into intermediate decision tables, such as Table 3, which helps in selecting the type of mandrel (T_m).

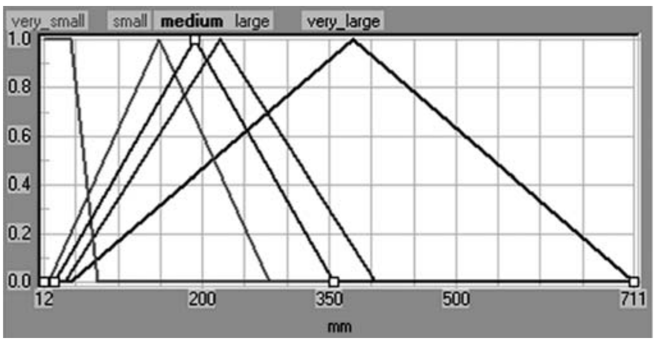

Fig. 6. Membership functions for fuzzification of the input variable centre-line radius, CLR

Table 2. Output variables of the fuzzy design system, with indication of the defuzzification method

OUTPUT			
Variable		Unit	Type
Number of mandrel balls	Bm	no	Centre of maximum
Length of clamping die	Lcd	–	
Length of wiper die	Lwd	mm	
Mandrel tangent setting	Sm	mm	
Type of mandrel	Tm	–	Fuzzy input/ Fuzzy output
Type of pressure die	Tpd	–	
Use of wiper die	Wd	–	

Finally, all the intermediate decision tables have been used for building the six rule blocks of the fuzzy system and for deciding the degree of support (DoS) of each rule. As an example, a portion of the rule block for the selection of T_m and W_d is pictured in Fig. 7.

The designed fuzzy system, as further shown in the following Sect. 4, has been used a number of times with changing tube geometry and material and produced encouraging results, since it always provided a feasible process with a sound product. However, in order to verify if the degree of support of each rule has been correctly evaluated, the system has been interfaced with a neuro-fuzzy learning module, provided by the mentioned software package. A few parts of the fuzzy system have been excluded from learning, since the author is very confident in their formulation. The system has been trained with the available experimental data. The neuro-fuzzy training showed no significant change in the DoS. This results is probably explained by the fact that the same experimental data, although combined with other sources, has been

Table 3. A small extract from one of the decision tables used for the selection of Tm (mandrel type)

		Degree of bend: DoB = CLR/OD				
		1	2	3	4	5
Wall factor WF = OD/t	0	M	M	P		
	20	M	M	M	P	
	30	M	M	M	M	M
	70	TW	M	M	M	M
	100	TW	TW	M	M	M
	125	TW	TW	TW	M	M
	200	TW	TW	TW	TW	TW
	225		UTW	TW	TW	TW
	275		UTW	UTW	UTW	UTW

#	IF DoB	RISKflat	RISKthin	RISKwrink	WF	THEN DoS	Tm
43	max				term5	1.00	M
44	max				term6	1.00	M
45	max				term7	1.00	M
46	max				term8	1.00	M
47				medium		0.60	M
48				large		0.90	M
49		large				0.33	M
50		very_large				0.33	M
51	min				term6	0.70	TW
52	min				term7	0.80	TW
53	min				term8	0.90	TW
54	min				term9	1.00	TW
55	verylow				term6	0.80	TW
56	verylow				term7	0.90	TW
57	verylow				term8	1.00	TW

Fig. 7. A small extract from one of the rule blocks

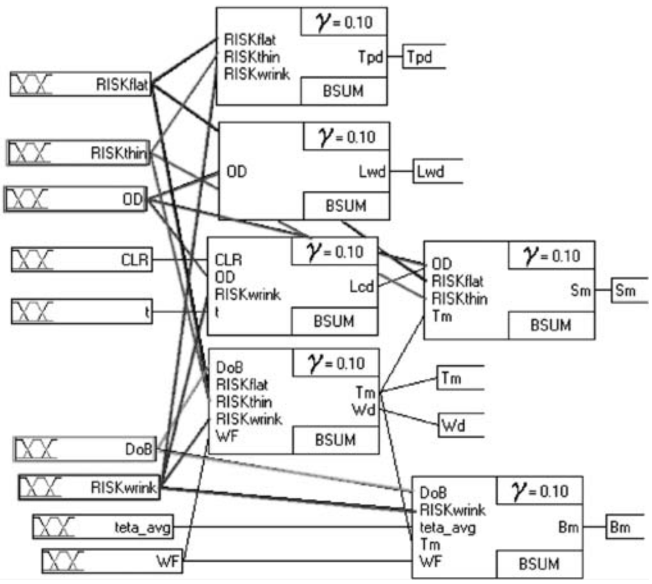

Fig. 8. Structure of the fuzzy logic system

used for manually designing the fuzzy system. Nevertheless it cannot be excluded that, in the future, training the system with a more extensive data set would produce different results.

Figure 8 shows the whole structure of rule blocks, identifying the fuzzy logic inference flow from the input variables to the output variables. The connecting lines symbolise the data flow. Every output variable is connected to only one rule block.

Within all rule blocks, the compensatory operator GAMMA (with parameter $\gamma = 0.10$) has been used for input aggregation, i.e. for the calculation of the "IF" part of the rule blocks.

As for result aggregation, the fuzzy composition combines the different rules to one conclusion: the BSUM method is used, meaning that all firing rules are evaluated. The degree of support (DoS) is used to weigh each rule according to its importance. The default value of an output variable is used if no rule is firing for this variable.

Different methods can be used for the defuzzification, resulting either in the most plausible result or the best compromise. The best compromise is produced by the centre of maximum (CoM) method, used in this context. As well as for input variables, the membership functions of the output variables are not uniformly distributed.

Further insights into the methodologies used for defuzzification in the proposed fuzzy system can be found in [18].

4 Application of the methodology

The described methodology has been implemented in a software tool (called Tube ProDes). The software has been developed, tested and evaluated exclusively with reference to stainless and carbon steel tubes, with changing wall factor. No other material has been tested. In the following, two examples of application of the software are presented.

4.1 Example 1: carbon steel tube with large wall factor

Tube ProDes has been tested with a dual phase steel tube with wall factor (OD/t) WF = 20 and degree of bend (CLR/OD) DoB = 1.96. Material properties and geometrical input data are given in Table 4.

The suggested overbending ratio is 1.041; the correct (experimentally verified) coefficient is 1.035.

The flattening indicator is $\text{Risk}_{flat} = 0.65 > 0.5$ (positive and greater than 0.5). This indicates that flattening will probably occur, regardless of the tooling setup.

The calculated wrinkling indicator is $\text{Risk}_{wrink} = 0.34$, which is positive, but smaller than 0.5. This indicates that wrinkling is likely to appear, but it might be reduced or suppressed with a proper tooling selection. Besides, the sensitivity of the process to a change in the strain hardening exponent n is low, since Δn_wrink = 45%. Thus, a correct selection of the tooling should be able to ensure an unwrinkled and robust process.

A comparison between the tooling designed by a process engineer and the tooling designed by Tube ProDes is briefly reported in Table 5. The tooling designed is simpler than the one selected by Tube ProDes.

It has been experimentally verified that, if using the tooling designed by the process engineer, the measured flattening is $\delta = 2.26$ mm, greater than the prescribed maximum admissible diameter reduction (2 mm). Besides, wrinkles grow on the inner tube profile (Fig. 9). If using the setup suggested by Tube

Table 4. Input data to Tube ProDes for example 1

Geometrical input		Material input	
Outer diameter OD	30 mm	Young modulus E	200 000 MPa
Wall thickness t	1.5 mm	Tensile strength UTS	660 MPa
Bending radius CLR	60 mm	ε_0	0
Bending angle θ	90°	Strain hardening exponent n	0.138
Max reduction on diameter δ	2 mm	Strain hardening coefficient K	996 MPa

Table 5. Tooling design suggested by Tube ProDes and by a process engineer for example 1

Tooling design	TuBe ProDes	Process engineer
Mandrel type (see Fig. 5) Tm	Close pitch (with Bm=4)	Formed end plug
Mandrel setting Sm	3.46 mm	7 mm
Wiper die Wd	yes	no
Pressure die (see Fig. 3) Tpd	roller	roller

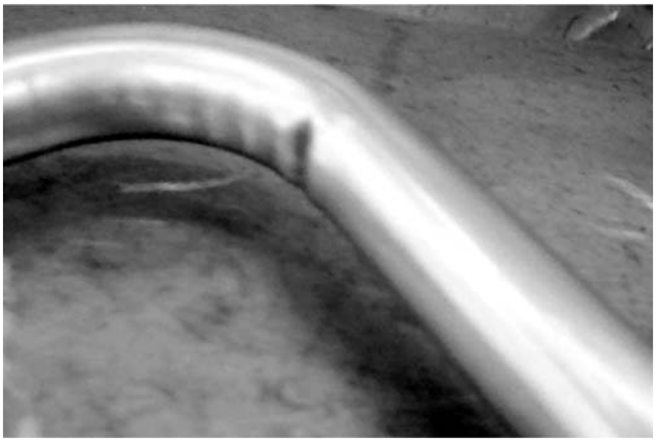

Fig. 9. Wrinkling on example 1

ProDes, flattening is closer to tolerance and no wrinkling is visible.

4.2 Example 2: stainless steel tube with small wall factor

Tube ProDes has been tested with a stainless steel tube with wall factor WF = 7 and degree of bend DoB = 2. Material properties and geometrical input data are given in Table 6. The overbending ratio, suggested by TuBe ProDes is 1.044, whereas the correct (experimentally tested) coefficient is 1.047.

The calculated thinning and wrinkling indicators are well below zero (−0.68, −0.50, respectively). Thus, there is no risk of these two defects even with a basic tooling , and the sensitivity of the process to a change in the material properties is not relevant.

Table 6. Input data to Tube ProDes for example 2

Geometrical input		Material input	
Outer diameter OD	6.35 mm	Young modulus E	193 120 MPa
Wall thickness t	0.914 mm	Tensile strength UTS	625 MPa
Bending radius CLR	12.7 mm	ε_0	0.0114
Bending angle θ	90°	Strain hardening exponent n	0.336
Max reduction on diameter δ	0.3 mm	Strain hardening coefficient K	1262 MPa

Table 7. Tooling design suggested by Tube ProDes and by a process engineer for example 2

Tooling design	TuBe ProDes	Process engineer
Mandrel type (see Fig. 5) Tm	Standard pitch (with Bm = 2)	Formed end plug
Wiper die Wd	no	no
Pressure die (see Fig. 3) Tpd	roller	follower

On the contrary, the flattening indicator is 0.64, which is positive and above 0.5.

A comparison between the tooling designed by a process engineer and the tooling designed by Tube ProDes is briefly reported in Table 7. The experiments show that, if using the setup suggested by the process engineer, the measured flattening is $\delta = 0.33$ mm, which is greater than the prescribed maximum admissible diameter reduction (0.3 mm). No significant wrinkling or thinning appears.

5 Conclusions

A comprehensive computer based approach for the automatic process design of rotary draw bending of tubes has been described, based on a combination of numerical calculation, fuzzy logic and empirical rules. The proposed method is able to correctly predict the risk of the occurrence of defects. Besides, it seems to be able to perform an effective design of the tooling setup. It has been used a number of times at an Italian company (Sicamb of Latina, Italy, hereby thanked and acknowledged), with changing tube geometry and material and produced encouraging results, since it always provided a feasible process with a sound product.

A limitation of the proposed approach is that the economical feasibility and convenience of the solution is not automatically evaluated. Currently, cost constraints are being tentatively included in the system.

References

1. Al-Qureshi HA, Russo A (2002) Spring-back and residual stresses in bending of thin-walled aluminium tubes. Mater Des 23:217–222
2. Al-Qureshi HA (1999) Elastic-plastic analysis of tube bending. Int J Mach Tools Manuf 39:87–104
3. Elchalakani M, Zhao XL, Grzebieta RH (2002) Plastic mechanism analysis of circular tubes under pure bending. Int J Mech Sci 44:1117–1143
4. Kim YM, Kim JI (2001) An analysis to minimize the amount of spring back after coiling of helical steam generator tubes. Int J Press Ves Pip 78:11–17
5. Peek R (2002) Wrinkling of tubes in bending from finite strain three-dimensional continuum theory. Int J Solids Struct 39:709–723
6. Tang NC (2000) Plastic-deformation analysis in tube bending. Int J Press Ves Pip 77:751–759
7. X. Wang X, J. Cao J (2001) Wrinkling limit in tube bending. J Eng Mater Technol 123:430–435
8. Wierzbicki T, Sinmao MV (1997) A simplified model of Brazier effect in plastic bending of cylindrical tubes. Int J Press Ves Pip 71: 19–28
9. Flehming T, Blumel KW, Kibben M (2001) Investigation to bending boundaries of circular tube cross sections and presentation of a new bending mandrel. In: Siegert K (ed) Hydroforming of tubes, extrusions and sheet metals. Mat-INFO, Frankfurt, pp 41–62
10. Alcoa Aluminum (1974) Forming Alcoa Aluminum. Alcoa Aluminum, Pittsburgh, PA
11. Miller GG (2003) Tube forming processes, a comprehensive guide. Society of Manufacturing Engineers, Dearborn, MI

12. Tapper JA (2001) Optimize your tube-bending operations. Met Form Mag June:66–72
13. Bouzakis K-D, Korlos A et al. (2000) Development of a technological post processor to improve the multi axis bending accuracy of furniture tubular components based on a process FEM simulation. In: IInd International Seminar on Improving Machine Tool Performance, Nantes-LaBaule, France, July 3–5, 2000
14. Jina Z, Luob S, Daniel Fang X (2001) KBS-aided design of tube bending processes. Eng Appl Artif Intell 14:599–606
15. Abdei-Malek K, Maropis N (1998) A design-to-manufacture case study: automatic design of post-fabrication mechanisms for tubular components. J Manuf Syst 17(3):183–194
16. Zambelli P (2003) Progettazione del processo di curvatura di tubi rotary draw bending. Master thesis, Università di Cassino
17. Banabic D, Bunge H-J, Pohlandt K, Tekkaya AE (2000) Formability of metallic materials. Springer, Berlin Heidelberg New York
18. Von Altrock C (1996) Fuzzy logic and neurofuzzy applications explained. Prentice-Hall, New York