Experimental and numerical analysis of roll bending process of thick metal sheets

A Mercuri\textsuperscript{1}, P Fanelli\textsuperscript{1}, F Giorgetti\textsuperscript{1}, G Rubino\textsuperscript{1} and C Stefanini\textsuperscript{1}

\textsuperscript{1} Department of Economics, Engineering, Society and Business Organization, University of Tuscia, Largo dell’Università, 01100 Viterbo, Italy
E-mail: alessandro.mercuri@unitus.it

Abstract. In metalworking, bending forming processes are used extensively for a wide range of applications referring to several industrial fields, such as oil&gas field, naval field or automotive field. In cylinders and truncated cones bending process, three-point roll forming of metal sheets represents a concrete option, which mainly consists of pyramid-type machines made of two lower rolls and a top roll. Each roll can be designed to work as a driven roll or as an idler and to move both vertically and horizontally during the rolling process, depending on the sheet and final product features (mechanical properties, thickness and final curvature mainly). Final products can be affected by defects, which represent a concrete problem for metalworking industries because of the further works to be done to meet customers needs; in three-point roll bending, warping defect and hourglass (or barrel) defect represent two of the most common problems. In this paper, an experimental and numerical analysis is proposed to detect defects on roll-bent thick cylinders referring to several companies experiences; the occurrence of thickness variability and circumferences variability along cylinder length and considerable differences between the internal and external length of cylinders themselves, referable to the so-called "hourglass defect" represents a common problem in this industrial field and a major cost for metalworking companies. A Finite Element (FE) 3D model of both the roll-bending machine and the metal sheet is used to simulate the mechanical behaviour of the metal sheet during the forming process, checking for the influence of the spring-back effect and the bending moments from the rolls. Both the pre-bending and the roll bending phases have been simulated. Rolls are modelled as rigid. Both rolls and sheet have been modelled using solid elements and contact elements to take into account rolls/sheet friction. Obtained results are compared with experimental results to check the reliability of the FE model and the simulation. The model itself is then implemented with a central lower roll which serves as an idler and is placed half-way between the original ones. The updated model is then used to simulate the process again and test the central idler as an hourglass-defect solution.

1. Introduction

Several systems and structures from different engineering fields require for the use of various-sized tubes and cylinders. Typical examples of such products applications include oil&gas ribs or the realization of civil infrastructures and edifices. Metalworking industries often work on this kind of products; their manufacture requires the forming of sheets to circular sections through bending processes (i.e. stamp bending, stretch bending) and a subsequent weld, to obtain the final artefact. Roll bending represents a concrete option for this kind of works; such process is mostly employed for plates and sheets bending and can be used for final products characterized by a wide range of bend-radius. Moreover, roll bending process ensure the high quality of the
final product, considering the high affordable dimensional accuracy, and requires a small space in workshops if compared with processes used for the same products [1]. The most simple configuration, the three-roll pyramid, is also the most used in metal carpentry factories; on the other hand, considering the wide range of final products geometry and dimensional accuracy requirements, different roll bender configurations have been designed and constructed over time, such as two-roll and four-roll benders. Both three and four-roll benders can be used on both symmetrical and asymmetrical configurations of rolls; besides, rolls can be driven (through mechanical, hydraulic or electromechanical systems) or be used as idlers. Three-roll benders are typically used to bend thick plates, while four-roll benders have been developed to satisfy specific workpiece requirements, e.g. the reduction of straight ends to be removed after bending. Nevertheless, although roll bending can be considered a simple technique for sheets forming, the theoretical analysis and process modelling (in which acting loads, geometry and dynamic features play a key role as parameters), are the main topics of several works since the 60s. First issues concerned the measurement of main loads (i.e. upper roll vertical force and driving torque) in a three-roll bender with pyramid configuration in case of plate forming [2]. In [3] a complete analysis of the single-pass three-roller pyramid roll bending geometry is proposed, considering bending as an elastoplastic process and a triangular moment distribution between rolls. Both the bending force and the moment are obtained by taking into account the shift of the contact point between the top roll and the metal sheet. Also in [4] three-roll benders are investigated, proposing an analytical method for bending moment and curvature distribution calculation in case of U-shaped cross-section plates, referring to top roll displacement and lower rolls rotation as parameters. A relationship between bending moment and final product curvature is established, which allows the build of a process model focused on process geometrical parameters and their application in a real-time control system. Several studies regard a specific process parameter or phase, e.g. in [5] an analytical approach for the evaluation of top roll position is suggested to achieve a specific bend radius in three-roll plate-bending, in case of multiple pass forming, also considering the change of Young modulus under deformation. In [6] there is a focus on thin plates forming through roll bending and the presence of the straight end. Another important investigation topic is the presence of defects and the build of real-time systems for their reduction; defects have been analysed in several works focused on different roll-bending configurations, in terms of roll-bender rolls number (two, three or four rolls) and position (symmetrical or asymmetrical), process temperature and sheet thickness [7]; also the link between these defects and the residual stress and strain field has been investigated [8]. The effectiveness of the above-mentioned models in detecting main parameters roles in bending process and the need for strong control on the process itself to avoid defects and increase bending velocity inspired several issues concerning specific roll-bending application models, e.g. symmetrical roll bending of cylinders [9], asymmetrical bending of cylinders [10] or bending of cones [11]. Moreover, control systems have been developed in case of both cold [12][13] and hot roll forming [14][15]. Regarding four-roll bending, a basic contribution came from [16], in which the bending scenarios of this kind of benders are exploited, and from [17], in which most relevant influential parameters are found and an effective model for four-roll bending is proposed. Generally speaking, nowadays numerical simulations play a central role in roll bending studies, in particular for the first evaluation of purposed analytical models. Finite Element (FE) simulations can be considered as the most reliable way for a priori models evaluation and resolution of most common roll bending process industrial issues. An important contribution came from [18], in which an innovative roll forming analytical model is proposed for the solution of several open issues in this field; in this case, FE modelling and experimental campaigns were carried out for the evaluation of innovative roll bending designs. Also in [19] FE modelling plays a key role, by allowing the analysis of the plastic deformation mechanisms for the cold ring rolling process.

In this paper, the problem of defects in case of roll bending of thick metal sheets is faced; in
a first time, an experimental campaign has been carried out during a three-point roll-bending process by measuring main geometrical parameters on both the roll bender (i.e. rolls diameters) and the product: as a sheet before the process and as a cylinder after the bent. Moreover, the roll bending process is recorded with a thermal camera, searching for possible temperature gradients on both the roll bender and the sheet. Referring to the obtained measurements, the presence of dimensional defects emerged as cylinder thickness and circumference variation along its length and as length differences between inside and outside the cylinder. This evidence led to the preliminary investigation of defects causes and possible solution effectiveness. Through Finite Element (FE) method, an effective numerical model of the three-point roll bending process is built and bending phases and results, including defects, are simulated. This model becomes the base for the analysis of bent lamina mechanical behaviour and defects causes. One of the most valuable solutions is the use of a central bottom idler roll, which makes the three-point roll bender a four-point roll bender. The so-modified roll-bending system is then modelled as a FE model and the roll-bending process is simulated, to investigate a possible reduction in previously detected defects.

2. Roll bending process

Multipass three roll-bending consists of three main phases. The first one is the pre-bending phase, in which one or two metal sheet edges are roll-bent to obtain small curved zones to be used as a first rolled part in the second phase, the roll-bending of the whole sheet. In pre-bending, the rolls are used in asymmetrical configuration (Fig. 1a), where one of the bottom rolls is closer, along the x-direction, to the top roll-abscissa. This position allows the bending of a small zone.

![Pre-bending phase](image1)

![Roll bending phase](image2)

Figure 1: Bending phases of roll bending process

The second phase consists in the roll-bending of the whole metal, which could be done through several rolls configurations, such pyramidal configuration provides for an equal x-distance of bottom rolls from top roll-abscissa, or symmetrical configuration (Fig. 1b). In this work, a roll-bending process obtained through a pyramidal configuration is investigated. This process can be carried out in a single pass or multiple passes. At the end of the roll-bending phase, cylinder straight edges could be cut and the cylinder edges are welded together. Finally, a further calibration could be done to reach the desired dimensions of the product. Despite the need for strict control on cylinders final shape to meet buyers needs, process key-parameters, such as rolls velocity or displacements, are nowadays decided by workers based on their own experience in absence of a unification.
2.1. Bending key factors

Material properties strongly influence its forming limits (i.e. ductile metals are easy to bend than brittle ones). In cold processes, there is no dynamic recrystallisation and no stress field reduction. Also hardening plays a key role in bending; a significant hardening implies a higher difference between yield stress and ultimate stress, higher elongation and a lower necking. Sheet stress field is another key factor, considering that biaxial stress reduces material ductility. In case of a sheet length which is ten or more times higher then the thickness, a plane strain field can be considered. Strain distribution is highly influenced by lamination direction. During lamination, crystal grains and impurities are stretched in this direction. This modification in grains aspect ratio leads to the sheet anisotropy. Consequently, material behaviour changes with the bending direction (which could be parallel or orthogonal to the lamination direction). Minimum bending radius has a central role between bending parameters. Under minimum bending radius, fractures will appear in correspondence with the external fibres, which are subjected to traction. Theoretically, internal and external fibres should have the same deformation (except for the sign of the deformation). In practice, during the process, the neutral fibre moves to the internal zone and the bending length is lower in the external zone. This deformation gap increases with the bending radius/thickness ratio ($r/s$). In most bending processes, friction plays a minor role; roll bending represents an exception, considering that consistent friction is required to move the sheet during rolling.

3. Experimental tests

The first part of the here-presented work consists of an experimental campaign based on the multipass three-point roll bending of a thick metal sheet through a pyramidal configuration. As mentioned above, also in most important metalworking industries usually there is no unification for roll bending process key-parameters, such as rolls velocity or displacements, the definition of whom relies on workers experience.

The campaign could be ideally divided into four parts: in the first part, measurements of metal sheet geometry are taken before bending; in the second part, the pre-bending process key-parameters are measured, including process velocity, rolls position and pre-bent area bending radius. Then, roll bending phase main process parameters, in particular top roll vertical displacement, bottom rolls position and process velocity, are acquired during the process. Furthermore, during the roll bending process the thermal camera Flir A655 is used to record local temperature along the sheet and rolls during bending; - in the third part, most relevant geometric measurements on the final product are taken, taking into account geometric parameters which could act as markers of cylinder defects.

3.1. First phase

In the first phase of the experimental campaign, key geometrical parameters for both the roll bender and the metal sheet are measured.

Available roll bender configuration includes a top roll ($TR$) and two bottom rolls (bottom left roll, $BLR$, and bottom right roll, $BRR$); most relevant dimensions are summarized in Tab. 1.

| $D_{TR}$ [mm] | $D_{BLR}$ [mm] | $D_{BRR}$ [mm] |
|---------------|----------------|-----------------|
| 1750          | 860            | 860             |
On the other hand, chosen thick metal sheet is made of SA5 16 GR 70 steel, the mechanical properties of whom are listed in Tab. 2.

Table 2: SA5 16 GR 70 mechanical properties

| Property                | Value  |
|-------------------------|--------|
| Young modulus (E) [MPa] | 210000 |
| Poisson ratio (ν)       | 0.3    |
| Tensile strength (σ_R)  | 506    |
| Yield strength (σ_S)    | 310    |
| Shear modulus (G) [MPa] | 505    |

Table 3: Pre-process metal sheet measurements

| L [mm] | W [mm] | Δ [mm] |
|--------|--------|--------|
| 9000   | 3594   | 147.5  |

As it can be seen in Fig. 2, the sheet has been ideally divided into rows along the length L (represented by numbers) and columns along the width W (represented by letters); this choice is linked to the need for marked points for measurements to be done before and after the bending process, such as thickness (Δ) ones. A summary of the obtained measurements is reported in Tab. 3.

Figure 2: Metal sheet dimensions and subdivision in rows (numbers) and columns (letters)

3.2. Second phase

The second phase of the tests firstly consists of the measurement of the key-process parameters during and after the pre-bending process. As mentioned above, pre-bending allows the bending of a near-edge zone of the sheet to simplify the start of the roll-bending of the rest of the metal sheet and can be realized on one or two sheet edges. Rolls positions, typical of an asymmetrical configuration, are summarized in Tab. 4. Most important process parameters, i.e. process velocity and final bending radius obtained, are collected in Tab. 5.
Table 4: Rolls positions - Pre-bending phase

| Roll                     | X-Position (mm) | Y-Position (mm) |
|--------------------------|-----------------|-----------------|
| Top Roll (TR)            | 0               | -18.5           |
| Bottom Left Roll (BLR)   | 603.0           | 0               |
| Bottom Right Roll (BRR)  | 1101.0          | 0               |

Table 5: Pre-bending key-parameters

| Process velocity [mm/min] | Bending radius [mm] |
|---------------------------|---------------------|
| 112                       | 1000                |

Key process-parameter measurements are also taken during roll-bending process and consist of both process-parameter and thermal measurements. Rolling velocity, top roll displacement and bottom rolls distance, are recorded for each bending pass; from Tab. 6, it is clear that process velocity and bottom rolls distance are constant during the whole process, while the top roll gradually goes down and increments the pressure on the bent sheet (see Tab. 7). Thermal measurements are taken through the Flir A655 thermal camera, which allows both the thermal video record and the numerical temperature local data collection during the whole process (see Fig. 3). As can be seen, a temperature difference exists between cylinder edges and centre, where the first zone shows a clear overheating of around 3°C. This difference can be linked to a possible higher crushing (and friction) on the edges, induced by the higher tendency to the radial displacement of the edge zone.

Table 6: Rolls positions - Roll bending phase

| Roll                        | X-Position (mm) | Y-Position (mm) |
|-----------------------------|-----------------|-----------------|
| Top Roll (TR)               | 0               | see Tab. 7      |
| Bottom Left Roll (BLR)      | -851.0          | 0               |
| Bottom Right Roll (BRR)     | 851.0           | 0               |
Table 7: Top roll displacement - Roll bending phase

| Pass | Displacement (mm) |
|------|-------------------|
| 1    | 94                |
| 2    | 22                |
| 3    | 25                |
| 4    | 20                |
| 5    | 15                |
| 6    | 10                |
| 7    | 6                 |
| 8    | 4                 |

Figure 3: Caption from thermal shooting of roll bending process
3.3. Third phase
The third phase of the experimental campaign includes the measurements on the final product, i.e. a thick cylinder, regarding the most important parameters for the evaluation of process quality. Firstly, a remarkable difference is found between cylinder internal and external length (Tab. 8); this difference can be linked to the rotation along circumferential direction of the sections orthogonal to the axis and nearby the edges during bending.

Table 8: Cylinder measurements - Lengths

| Internal length [mm] | External length [mm] |
|----------------------|----------------------|
| 1                    | 3603                 |
|                      | 3596                 |

Table 9: Cylinder measurements - Internal diameter

| Position | $D_{int}$ [mm] |
|----------|----------------|
| A        | 2754           |
| B        | 2740           |
| D        | 2750           |

Table 10: Cylinder measurements - External circumferences

| Position | $C_{ext}$ [mm] |
|----------|----------------|
| left A   | 9570           |
| right A  | 9550           |
| B        | 9590           |
| right D  | 9590           |
| left D   | 9590           |

Table 11: Cylinder measurements - Thickness

| Row | left A [mm] | A [mm] | B [mm] | D [mm] | right D [mm] |
|-----|-------------|--------|--------|--------|--------------|
| 3   | 146.00      | 147.28 | 146.82 | 146.48 | 143.92       |
| 5   | 145.01      | 146.98 | 146.6  | 146.11 | 143.61       |
| 6   | 144.42      | 146.73 | 146.86 | 146.5  | 144.37       |
| 7   | 145.17      | 147.05 | 146.86 | 146.42 | 144.05       |

Another appreciable variation is detected in both the internal diameter ($D_{int}$) of the obtained cylinder along the length (Tab. 9) and external circumference values ($C_{ext}$) along the length (see Tab. 10). The first in-homogeneity clearly shows the presence of the hourglass shape on the product, considering that the internal diameter on the central position (pos. B, see Fig. 2) is smaller than on the edges (pos. A and pos. D). External circumferences analysis shows a relevant
mismatch between pos. A (i.e. cylinder left edge) and other position measurements. This evidence remarks the tendency to the hourglass shape, but also a difference in sheet mechanical behaviour between the edges.

A remarkable variation of cylinder thickness along its length can be observed in Tab. 11; it is clear the higher thickness reduction of the cylinder right edge (pos. D), which is evident in rows 3, 4 and 5 measurements. This can be linked to the above-mentioned mechanical behaviour of sheet at the edges. If compared with pos. A (sheet left edge), pos. C zone seems to be better constrained in radial direction, with a consequential reduction in sheet thickness on this zone.

3.4. Experimental campaign conclusions
Referring to the above-reported measurements, it is clear that the roll bending process, with the tested configuration, can not guarantee a final product which is strictly consistent with the geometrical requirements. In particular, some key-parameters, such as thickness, internal diameter, external diameter and length are not homogeneous along the cylinder length and a deviation of cylinder shape to an hourglass shape can be detected. Moreover, thermal video footage of the roll bending process remarks the presence of a thermal gradient along the cylinder length, considering that the edges are overheated than cylinder centre; this evidence is probably related with the higher crushing of cylinder edges and the consequent increment in friction.

These deviations represent concrete defects for metalworking industries and require for further processes to reach buyers needs on final products; taking into account the high unit cost of each cylinder, this represents a significant cost for industries, which aim at the concrete solution for shape defects. For this reason, after the analysis of the experimental campaign results, numerical simulations are employed to get a preliminary comparison to detect possible solutions.

4. Numerical model and process simulation
A Finite Element (FE) 3D model of both the roll-bending machine and the metal sheet is used to get a preliminary analysis of the mechanical behaviour of the metal sheet during the rolling process. The first pass of the roll bending process is simulated. Both rolls and sheet have been modelled using solid elements and contact elements to take into account rolls/sheet friction. Obtained results are firstly compared with experimental results to check the reliability of the FE model and the simulation. The model itself is then implemented with a central lower roll which serves as an idler, whose axis is rigidly connected to top roll one in vertical displacement, and is placed half-way between the original ones, i.e. a four rolls roll-bender configuration is chosen. The updated model is then used to simulate the process again, to get a preliminary investigation on the effectiveness of the four-roll configuration for the reduction of the above-mentioned defects and get a preliminary test of the central idler as an hourglass-defect solution.

4.1. Roll bending FE model
The FE model of the three-point roll bending process is strictly related with the process reported in the experimental campaign chapter, in terms of roll-bender geometric features, of metal sheets (i.e geometry and material mechanical properties) and of process parameters (i.e. bottom rolls abscissa-position during bending and top roll displacement during the process). Taking advantage of the longitudinal metal sheet symmetry, the model includes only half of the experimental campaign setup (roll bender and sheet), to reduce the computational burden. The FE model of the four-point roll bending process is similar to the three-point roll bending one, with the only exception of the presence of the bottom central roll, which acts as an idler and is joint to the top roll to have the same axis displacement.

First of all, the rolls are modelled as rigid; this represents an approximation which can be used taking into account that the presented work represents a preliminary evaluation.
model is obtained through 3-D 8-nodes rigid solid elements; the mesh is finer near rolls surfaces, to improve rolls-sheet contact simulation. Model sheet dimensions and material properties (i.e. the linear elastic-perfectly plastic behaviour) are the same as the experimental campaign steel sheet. To obtain an accurate simulation of sheet deformation, 20 nodes quadratic 3D solid elements are chosen and an adequate mesh density applied. In contact simulation, sheet surfaces are modelled through contact elements, while rolls surfaces are modelled as a target; the contact is modelled as a node-to-surface contact model. Roll-bending process simulation provides for a sequence of static loadstep based on the features of the real process analysed during the experimental campaign. In a first step, the top roll goes down and gradually raises its pressure applied on the pre-bent area. In the second step, the top roll begins its rotation and, consequently, the bending phase begins. Considering that this work aims at a preliminary analysis, only the first pass of the roll-bending process is simulated. Furthermore, the pre-bending process is not simulated, considering that is mainly related to local effects.

4.2. Results analysis
Analysis results consist of a preliminary comparison of the sheet mechanical behaviour in case of three-point roll bending and four-point roll bending. In particular, this investigation deals with mechanical parameters which are strictly connected with the above-mentioned defects related to the hourglass-shape of thick cylinders. Considering the appreciable difference between internal and external length, related to the rotation of cylinder sections (caused by the bending induced by rolls), the investigation starts from the strain field along the axis. As can be seen from Fig. 6, the strain field is near zero on the whole sheet, except for the edge. In this zone, it is clear that the internal edge is subjected to traction, while the external edge is subjected to compression and their strains are similar in absolute value.

This evidence leads to the hypothesis of an edge-located strain due to the internal constraint of material which avoids the same deformation in other sheet zones. Moreover, the observation of the axial strain field obtained from the simulation of a four-point roll bending process suggests that the presence of the bottom central roll can represent a possible solution for internal/external length mismatch. Indeed, referring to Fig. 7, a reduction of the edge axial strain can be detected.
for both the internal (~17%) and the external edge (~25%).
This represents the first signal of the possible effectiveness of the tested solution; to extend the analysis and to get a comparison with experimental campaign data, the investigation on numerical simulations results also includes a study of the axial displacement field.

The reference to the axial displacement field allows comparing both numerical simulations and experimental campaign results, taking into account that numerical simulations are referred only to the first pass of the roll-bending process.
Fig. 8, referred to the three-point bent sheet, clearly shows that edge metal fibres are subjected to traction on the internal edge and compression on the external edge, as predicted by strain fields. This is the same evidence taken from the experimental measurements (see Tab. 8); moreover, the displacement values of the numerical simulation are lower, but it should be remembered that the numerical data are taken from one-pass process simulation.

In conclusion, the axial displacement field of the four-point bent metal sheet is investigated. Referring to Fig. 9, an appreciable reduction of the opposite axial displacements on the internal and external edges can be underlined. After the first roll-bending pass, the axial displacement
on the internal edge seems to be the same as the three-point bent sheet, while the external edge displacement shows a reduction of $\sim 70\%$. This is a remarkable result, which must be investigated referring to numerical simulations of the whole roll-bending process, to check: the convergence between the experimental data and numerical data concerning three-point bent metal sheet; the reduction of the cylinder internal/external length mismatch during the whole process in case of four-point bent sheets; the reduction of the axial displacement on the external edge in case of four-point bent sheets.

Referring to Tab. 9 and Tab. 10 emerges the need for an investigation on the variation of circumferences along the cylinder axis. Taking into account that numerical simulations include only the first bending pass, it is chosen to analyse the variation of the bending radius along the cylinder axis (the sheet width), considering some of the experimental measurement points themselves (rows and columns showed in Fig. 2). In particular, position B (half of the sheet), position C (halfway between the centre and the sheet edge) and position D (sheet edge) are chosen.

Table 12: Three-point bent sheet simulation - Bending radius

|          | A [mm] | C [mm] | D [mm] |
|----------|--------|--------|--------|
| Bending radius | 2276,75 | 2276,58 | 2280,91 |

Table 13: Three-point bent sheet simulation - Bending radius

|          | A [mm] | C [mm] | D [mm] |
|----------|--------|--------|--------|
| Bending radius | 2441,79 | 2440,12 | 2442,89 |

The analysis of Tab. 12 data confirms the tendency emerged from the experimental data; the bending radius in correspondence with the cylinder edge (pos.D) is higher than the other two, showing a clear trend to an hourglass-shape that is marked since the first process pass. Moreover, the comparison of the above-mentioned data with the ones presented in Tab. 13 confirm the suitability of the four-point roll bending process as an hourglass defect solution. In fact, data from the table show a substantial homogeneity of bending radius along with the chosen position, with a reduction of the before-remarked mismatch between radii of $\sim 33\%$.

5. Conclusions

This paper aims at a preliminary investigation on possible solutions for the reduction of the hourglass-shape defect on roll-bent thick metal sheets, which represents a problem for metalworking industries, considering the high unit cost of each cylinder and the further processes required to obtain the desired final shape. The first part of the here-presented work consists of the experimental campaign based on the three-point roll bending process of a thick steel sheet; in a first phase, roll-bender and sheet dimensions have been collected together with material properties for the bent sheet. In the second phase, key-process parameters during both pre-bending and roll-bending processes have been acquired and thermal video footage of the roll bending process has been recorded; acquired pictures remark the presence of a thermal gradient
along the cylinder length related with the higher crushing of cylinder edges and the consequent increment in friction. In the third phase, final product main geometrical features have been acquired; in particular, thickness, internal diameter, external diameter and length have shown variations along the cylinder length and a deviation of cylinder shape to an hourglass shape have been detected. The investigation on possible solutions for the emerged defects have been pursued through numerical simulations; a Finite Element model of both the roll-bender and the metal sheet have been built for the three-point roll bending process analysed during the experimental phase. The introduction of a bottom central roll has been detected as a possible solution for the appearance of the hourglass-shape defect; therefore, a Finite Element model of the four-point roll bender and the metal sheet have been built. Both of the roll-bending processes have been simulated for the first bending pass. The analysis of the obtained results has been firstly focused on the axial strain field, which remarks the presence of an edge-located strain and appreciable differences between internal and external edge strain on the three-point bent sheet, while the four-point bent sheet have shown an appreciable reduction of these differences. Moreover, these discrepancies have been also found during the investigation on the cylinder axial displacement: this represents a clear analogy with the mismatch of internal and external length underlined during the experimental campaign. Besides, the four-point roll bent sheet shows a remarkable reduction in the difference between internal and external axial displacement; this represents a preliminary confirmation of the potential effectiveness of this roll-bending setup as an hourglass-shape defect solution. A further proof of this potential has been found through the analysis of the bending radius of the bent sheet along metal sheet width (i.e. cylinder axis); on one hand, three-point roll bent sheet shows an higher bending radius on the edge than in the middle, which represents a partial analogy with the experimental data regarding circumferences variations along cylinder length. On the other hand, four-point bent sheet shows a consistent reduction in these differences. In a next phase of the here-presented work, the whole roll-bending process will be simulated for both the three-point and the four-point setup and a further investigation on key-parameters concerning sheet mechanical behaviour will be completed. Referring to the obtained result, the opportunity of further experimental campaigns will be evaluated.

Acknowledgements
This work has been realized in cooperation with AIPE (Associazione Italiana Pressure Equipment) and Walter Tosto S.p.A.; the authors want to thank both the project partners for their support.

References
[1] Hua M, Baines K and Cole I 1999 International Journal of Machine Tools and Manufacture 39 905–935
[2] Bassett M and Johnson W 1966 Journal of Strain Analysis 1 398–414
[3] Hansen N 1979 Journal of Engineering for Industry 101 305
[4] Yang M and Shima S 1988 International Journal of Mechanical Sciences 30 877–886
[5] Gandhi A and Raval H 2008 Journal of materials processing technology 197 268–278
[6] Cai Z Y and Lan Y W 2011 Analysis on the straight-end problem in thin-plate three-roll bending Applied Mechanics and Materials vol 80 (Trans Tech Publ) pp 585–590
[7] Tehrani M S, Hartley P, Naeini H M and Khademizadeh H 2006 Thin-walled structures 44 184–196
[8] Ktari A, Antar Z, Haddar N and Elleuch K 2012 Journal of mechanical science and technology 26 123–128
[9] Wang Y, Zhao L, Cui X and Zhu X 2019 Advances in Mechanical Engineering 11 1687814019847861
[10] Tran Q H, Champliaud H, Feng Z and Dao T M 2014 The International Journal of Advanced Manufacturing Technology 75 1233–1244
[11] Li Z, Yang H, Li H and Xu J 2010 Computational materials science 50 666–677
[12] Hardt D, Roberts M and Stelson K 1982
[13] Yang M, Shima S and Watanabe T 1990
[14] Voronin S S, Gasiyarov V R and Radionov A A 2016 A development of the method of the control signal
formation for the hot plate mill automation systems to improve the flatness of the finish plate. 

MATEC Web of Conferences vol 45 (EDP Sciences) p 04001

[15] Karandaev A, Loginov B, Radionov A and Gasiyarov V 2017 Procedia Engineering 206 1753–1760

[16] Hua M, Baines K and Cole I 1995 Journal of materials processing technology 48 159–172

[17] Hua M, Sansome D, Rao K and Baines K 1994 Journal of Materials Processing Technology 45 181–186

[18] Hu W and Wang Z 2001 International Journal of Machine Tools and Manufacture 41 731–747

[19] Guo L, Yang H and Zhan M 2005 Modelling and simulation in materials science and engineering 13 1029