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Dynamic detection of tubes wrinkling in three roll push bending

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Abstract

Three roll push bending allow to manufacture bent profiles used for structural or piping purposes in several industrial fields such as aerospace, automotive, energy and chemical. When thin-walled tubes are formed with small bending radii, the components may suffer of wrinkling at the intrados due to the critical compressive stress state induced by the deformation. Poor tuning of the bending parameters, tool wear, scatter of the tubes diameter and mechanical properties, erroneous positioning of the longitudinal seam weld compared to the bending plane can make it impossible to achieve the required accuracy and, more in general, the proper control of the process. The paper aims at proving the suitability of dynamic analysis techniques to detect the defects due to the instability of the tube sections during the process. The approach was applied to different industrial processing conditions and the results are compared and discussed. The proposed approach appears promising for the detection of wrinkling, once they appear on the tube, and capable to give accurate feedback for the real-time adjustment of the process parameters.

Keywords: tube bending; three roll push bending; wrinkling, vibrations

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Nomenclature

R_f	Tube curvature radius
φ	Forming roll angle
X_{PC},$\dot{X}_{PC}$	Push carriage stroke, and push carriage speed
$Oxyz$	Global coordinate reference system
$Ox_1y_1z_1$	Local coordinate reference system
A_{x1}, A_{y1}, A_{z1}	Accelerations measured along the axes of the local coordinate reference system
$\dot{\theta}_{x1}, \dot{\theta}_{y1}, \theta_{z1}$	Angular rates measured around the axes of the local coordinate reference system
θ_z	Angle around the direction Z in the global reference system
W, GW	Pitch between of winkles and between group of wrinkles

1. Introduction

Three roll push bending (TRPB) is commonly used to manufacture complex-shaped tubular structures for a wide range of applications such as piping, architectural, land vehicles and aircrafts as well [1]. During the process, the tube is moved towards the bending and forming rollers by a push carriage, while one or more pressure rollers support the workpiece to prevent uncontrolled deflections in the straight part of the tube. A mandrel, made of a cylindrical rigid body and idle rings linked by spherical joints, may support internally the tube to prevent wrinkles and roundness defects of the profile sections during the deformation. Thanks to the process extreme flexibility, three dimensional freeform geometries can be obtained by the continuous adjustment of a unique set of forming rollers [2,3], combining more plane bends with the rotation of the bending plane around the tube axis [4]. However, the optimal setup and the process stability may be dramatically critic especially when thin-walled tubes are formed with small bending radii, due to the wrinkling at the intrados as consequence of the critical compressive stress state induced by the deformation. The setup of such processes is typically time consuming and requires long-term experienced operators to set the machine parameters; furthermore, the production stops may be frequent due to random factors (i.e. tool wear, scatter of the tube section accuracy and mechanical properties, non-systematic positioning of the seam weld compared to the bending plane) making impossible to achieve high accuracy and repeatability.

Off-line numerical and analytical design techniques, which aim at predicting the correct process parameters and tool geometries, have demonstrated strong limitations and little industrial appeal: they require accurate characterization of the material properties and can be extremely sensitive to the many input parameters, both numerical and experimental, not least the scatter of the material properties that can be frequent in small batch or discontinuous production [5]. Experimental investigations of the instability phenomena are mainly limited to the post-processing of the defect to evaluate their entity [6] or for the calibration of the numerical models [7], with little researches on the real-time control of the process or the automatic adjustment of the process parameters to compensate undesired deviations from the stable conditions. Some investigations about the possibility of controlling in real-time tube bending

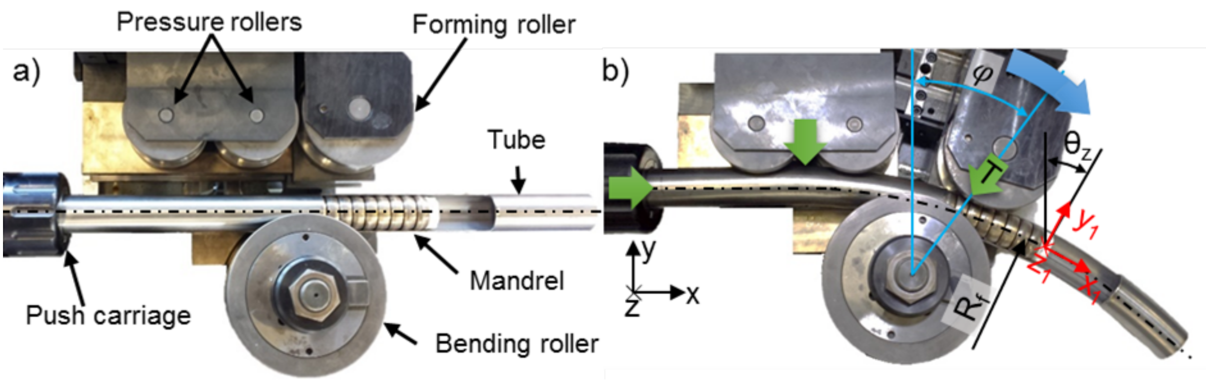


Fig. 1: a) Three roll push bending setup, with detail of the position of the mandrel inside the tube, b) tools kinematics and mandrel position in the deformed tube in the local and global coordinate reference systems.

processes address the springback detection and its compensation, but the developed techniques are limited to the use of contact probes [8] or off-line vision measurement systems [9], which typically require an adjustment of the production cycle or the use of structured light, difficult to manage in a production environment.

The approach presented in the paper aims at developing a real-time technique to detect the defects that can occur in the TRPB process due to the material instability limits, so to provide a prompt feedback to the machine CNC for the adjustment of the process parameters or the immediate stop of the production before the tool breakage. To this aim, an innovative smart mandrel that embeds dynamic sensors was implemented during industrial trial tests and the sampled data were real-time analysed in both the time and frequency domains. The paper is organized in two parts: the first sections introduce the application case and the main details of the experimental equipment; in the second part, with reference to the different wrinkling that were obtained, the main results of the data analyses are given and commented.

2. Application case

The application case refers to an AISI 304 tube, with a length of 2000(±1) mm, an outer diameter equal to 60.15(±0.10) mm and a thickness of 1.15(±0.10) mm, that was bent to a final radius R_f equal to 340 mm. Fig.1 a) shows the experimental setup with the main forming tools and the mandrel inside the tube that is fixed to a tie rod. The three roll push bending machine is a fully electric BLM Elect 63™, controlled by a CNC that can be programmed by the user thanks to a GUI and a specifically developed CAM. The tools consist of four rollers made of 40NiCrMo7 steel and a mandrel manufactured in the bronze alloy AMPCO M4 to avoid excessive wear due to the sliding with the tube inner walls. An inner mandrel with ten ring joints was used in all the tests, with a total length of the rings of 225 mm.

3. Experiments

3.1. Experimental equipment

An innovative smart mandrel was designed and developed in order to allow the real-time monitoring of the process, embedding an Inertial Measurement Unit (IMU) to measure the orientation of the bent tube section during or just after the bending stage. Such measurement position was evaluated as the most sensitive to the dynamic phenomena that can affect the machine during the tube bending and in [10] the performances were discussed when applied to similar tube bending processes. The IMU is a MPU-6050 device that mounts onboard a Digital Motion Processor™ (DMP™), three gyroscopes and three accelerometers that allow measuring respectively the angular rates $\dot{\theta}_{x1}$, $\dot{\theta}_{y1}$, $\dot{\theta}_{z1}$ and the accelerations A_{x1}, A_{y1}, A_{z1} of the measurement section around the axes X_1, Y_1, Z_1 of the local coordinate system as show in Fig.1 b). The IMU, based on MEMS technology, has a size of 20x15x10 mm and it is fixed inside a protective case on the last ring of the mandrel. The accelerometers were set to measure a range of ±2 g, while the gyroscopes to measure a range of ± 250 dps, with a 16-bit resolution per axis. The data sampled by the sensor, which has been previously calibrated through the procedure presented in [11], are recorded by a microcontroller with a frequency of 600 Hz. In the reference case, which consists in a planar bending in the *XY*-plane, the system allows the direct measure of the dynamic phenomena that arise during the process, while actual angle of the bent section orientation, θ_z [12] with respect to the fixed reference system *Oxyz* (see Fig.1 b) can be evaluated as:

$$\theta_z = \sum_{i=1}^{n} \left(\dot{\theta}_{z1i} \cdot \Delta T_i \right) \tag{1}$$

where ΔT_i is given by the sampling frequency.

3.2. Experimental plan

The tests were performed on the industrial machine described in section 2, equipped with the instrumented mandrel introduced in section 3.1. The rollers settings during the tests were intentionally chosen next to well-known critical conditions to obtain wrinkled tubes and compared to the standard condition of a sound part. Table 1 shows the investigated testing conditions that were achieved by increasing the forming roll angle in order to have a more severe deformation.

Table 1: Experimental plan

Test case #	Bending die angle (deg)	Push carriage speed (mm/s)	Wrinkling mode	Repeatability
1	8.3	210	Not wrinkled	10
2	10.4	210	Localized wrinkles	10
3	15	210	Spread wrinkles	10

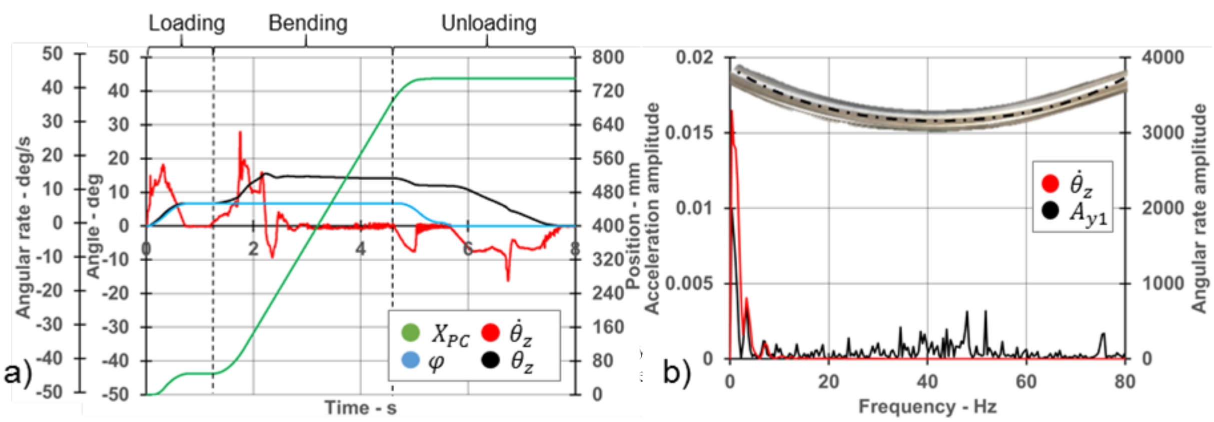
4. Results

The data sampled by the IMU and the tools position recorded by the CNC of the machine, were processed and merged together to analyze the signal during the different bending steps. Fig.2 a) shows the signal recorded for the reference case of the sound component without wrinkles. The process can be divided into three main steps:

- *loading*: when both the pressure and forming rollers reach their working position, the former by a translation along the direction y of the global coordinate reference system, the latter by a translation T and a rotation φ as shown in Fig.1 b);
- *bending*: in which the push carriage moves the tube towards the forming group, while the mandrel is kept at a fixed axial position inside the tube;
- *unloading*: after the forming step the rollers moves back to their initial position and the mandrel is withdrawn to enable the workpiece unloading.

4.1. Analysis in the time domain

Fig. 2 a), Fig. 3 a) and Fig. 4 a) show the signals, namely the angular rate $\dot{\theta}_z$ and the rotation θ_z, which are recorded in the three TRPB test cases reported in Table 1. In both the test cases #2 and #3, the first wrinkles were detected since the first loading step (see the negative peak of the angular rate $\dot{\theta}_z$ in Fig. 3 a) and Fig. 4 a)), at an approximate process time of 0.15 s. As the bending step starts and the tube is moved forward, in all the three testing conditions a positive value of the angular rate $\dot{\theta}_z$ is measured at the process time of about 1.2 s that corresponds to the beginning of the tube bending. Such signal does not correspond to any wrinkle, but is due to usual machine vibrations during the process.



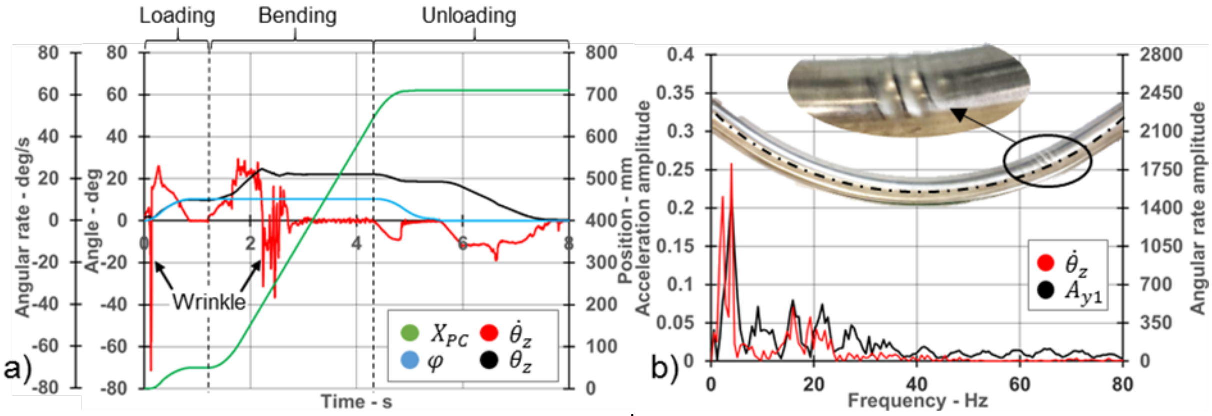


Fig. 3 a) Signals recorded during the TRPB process by the IMU, namely $\dot{\theta}_z$ and θ_z, and by the machine CNC motors, namely φ and $X_{PC,}$ b) spectrum of the angular rate along the Z direction and of the acceleration along the Y_I direction in a case with localized wrinkles.

The localized wrinkles were detected in the test case #2 as a negative peak shown of the angular rate $\dot{\theta}_z$ at the process time of about 2.3 s, see Fig. 3 a). For the test case #3, the spread wrinkles were indicated by multiple peaks of the angular rates, starting from a process time of about 2.3 s until the end of the bending step. For both the two examined test cases, it was seen that the computed angle θ_z showed little oscillations in correspondence of the acceleration peaks plotted in the time domain. The onset of wrinkles and the mandrel passage through them causes high discontinuities in the measured angular rate, which can be used to set proper criterion for stopping the production line.

4.2. Analysis in the frequency domain

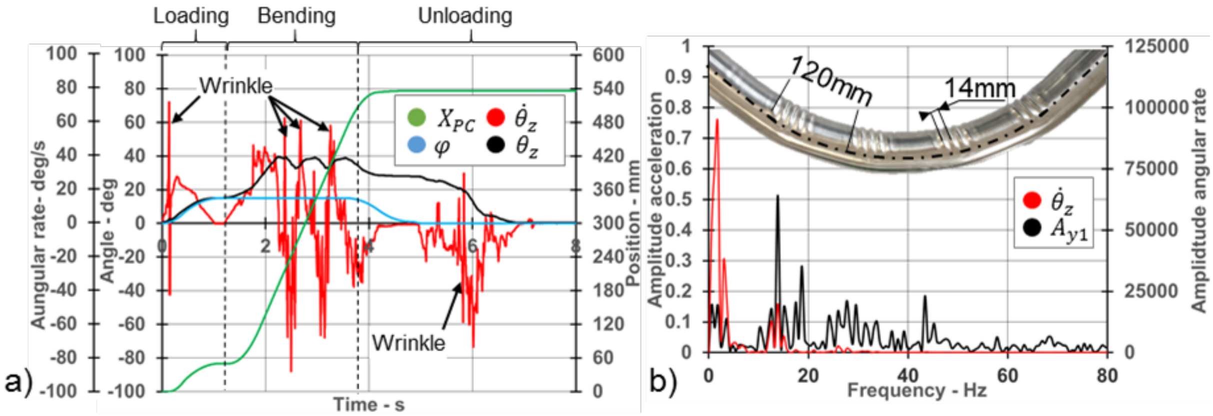


Fig. 4: a) Signals recorded during the TRPB process by the IMU, namely $\dot{\theta}_z$ and θ_z, and by the machine CNC motors, namely φ and $X_{PC,}$ b) spectrum of the angular rate along the Z direction and of the acceleration along the Y_I direction in a case with spread wrinkles.

The analysis of the only bending step in the frequency domain allows a further understanding of the instabilities that appear at the tube intrados. Fig. 2 b) shows the spectrum of the angular rate and the acceleration A_y along the y_I direction, in the test case #1, where no relevant peaks are detected. On the contrary, Fig. 3 b) and Fig. 4 b) show in the test cases #2 and #3, several peaks between 5Hz and 50 Hz corresponding to the defects that are detected at the tubes intrados. In particular, for the latter, the peaks of the angular rate at 1.85 Hz and 13.85 Hz can be related to the pitch between the wrinkles (W) and to the pitch between the groups of wrinkles (GW). Under the hypothesis of constant speed of the push carriage during the bending stage, equal to 210 mm/s, the pitch between the wrinkles can be calculated as:

$$W = \frac{\dot{X}_{pc}}{f_W} \tag{2}$$

$$GW = \frac{\dot{X}_{pc}}{f_{GW}} \tag{3}$$

where $\dot{X}_{PC}$ is the speed of the push carriage and f_W and f_{GW} are the frequencies of the wrinkles and the group of wrinkles obtained by the FFT analysis, respectively. The calculated values of 15.3 mm and 114 mm, respectively for the pitch between the wrinkles and the groups of wrinkles, are in good agreement to the values experimentally measured on the tubes equal to 14.3(±0.6) mm and 120.2(±1.2) mm. The in-line analysis of the spectrum of the measured signals can be used to automatically discard any faulty components.

5. Conclusions

The paper presents a new approach for the real-time identification of the wrinkles in TRPB processes based on the acquisition of vibrations and angular rates by means of an innovative smart mandrel. The mandrel embeds a Digital Motion Processor™, gyroscopes and accelerometers that allow measuring respectively the angular rates and the accelerations of the bent tube sections. Specifically developed algorithms allow the real-time time and frequency analysis of the signals by which accurate information about the defects occurrence and their position along the tube can be obtained. The time domain analysis of the angular rate can help determining the onset of wrinkles n the bending zone, while the analysis in the frequency domain can give an estimation of the distance between the defects and their frequency during the deformation.

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