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Calculation tool and closed loop control for the JCO® pipe forming process

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Abstract

In this paper, a new solution for the process planning and closed loop control of the JCO® pipe forming process is presented. JCO® pipe forming enables the production of open seam pipes out of steel plates by progressive bending (usually between 15 and 23 subsequent circumferential bending steps). Typical JCO® pipes can be found in a diameter range from 457 to 1422 mm (18 to 56 inch) with wall thicknesses of up to 45 mm. These longitudinal-submerged arc-welded (LSAW) pipes are usually 12.2 or 18.3 m long.
One crucial process parameter is the stroke for each single bending step depending on the required open seam pipe shape: With regard to subsequent process steps a perfect round shape is not always beneficial. Thus, the calculation software ShapeBase has been implemented into practice recently, taking into account the most important steps in the pipe production process chain. This fast software tool allows the process planning and optimisation of JCO® plate forming to pipe.
But due to variations in raw material (e.g. chemistry, yield point, wall thickness) even reliable theoretical calculations of process parameters can only be taken as initial machine values. To decrease further optimisation effort and increase the quality not only of the whole pipe lot but also of each single pipe, the above mentioned tool has been extended by an in-line measuring unit ShapeView and a real-time process control module ShapeControl.

Keywords: Pipe forming; bending; automation

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1. Introduction

To produce LSAW pipes the U-O bending, the three-roll bending (3-RB) or the JCO® process can be used. As reported in [1], the U-O process permits the highest production rates, of up to thirty-five pipes per hour, but has restricted flexibility, and requires high investment levels. The production rates of the 3-RB and JCO® process, investments for which are significantly lower, are up to fifteen and eighteen pipes per hour respectively. The JCO® process, unlike the 3-RB process, is capable of forming pipes of 18.3 m in length, with high wall thicknesses.

The requirements in the quality of the pipes are constantly increasing – particularly regarding the permitted geometric deviations. This is not only true for the pipes intended for the offshore market; also for some overhead lines, roundness deviations are limited to less than 0.75% of the diameter to further aid welding in the field.

Currently, a rapidly growing activity around the development of closed loop control systems in metal forming processes can be noticed [2]. However, regarding LSAW pipe production latest papers concentrated on optimized models for offline process calculations, e.g. [3]. Until now, both implementations and approaches on closed loop control systems regarding large diameter pipe properties can hardly be found.

2. Technological solutions in the manufacture of large-diameter pipes

Based on the computation model described in [4], the software system Shape was developed. It is intended not only for well-founded dimensioning of machines in the project phase of plant engineering but in particular for comfortable technological support in the determination and optimisation of machine parameters in practice. Here, special focus is on the JCO® forming press as core unit for forming: In the forming press, an open seam pipe is made from a steel plate with initially crimped edges in a defined sequence of bending steps, see Fig. 1(a). The software also considers the upstream and downstream machines in the process chain, such as the edge crimping press and the pipe closing press. This is essential because in many cases, the interrelations between the machines in the process chain must be considered and optimised. To adapt the system to the different theoretical and practical requirements in large-diameter pipe production, the entire system was subdivided according to functions. Accordingly, the Shape system shown in Fig. 1(b) consists of the three modules ShapeBase, ShapeView and ShapeControl.

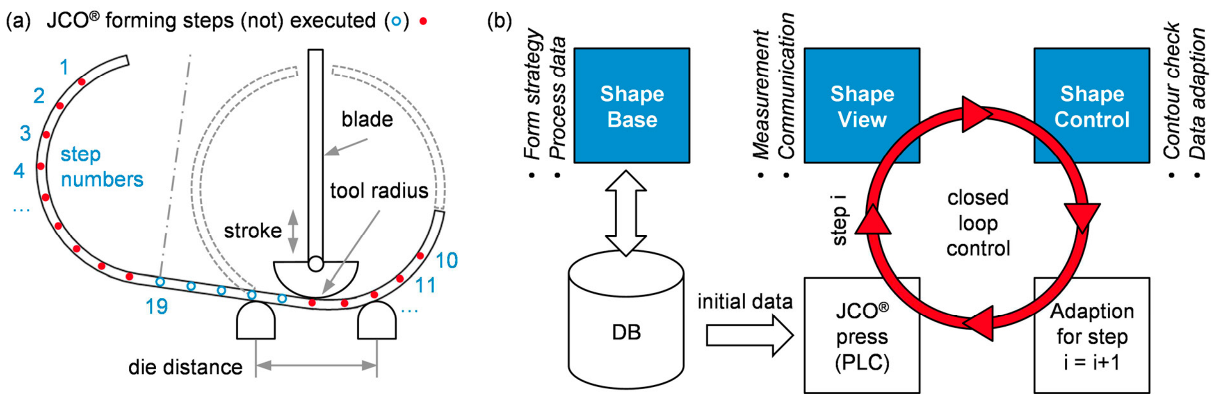

Fig. 1. JCO® forming process (a), interaction of the Shape modules for process control (b)

The ShapeBase module – a semi-analytical process model – is used for all forming calculations and optimisations based on [4] and calculates the machine parameters. The ShapeView module measures the current pipe contour during the forming process. The compact laser measuring unit is arranged in the forming area in such a way that it can provide contour measurements of the current forming zone and the adjacent areas without any loss of cycle time. The contour data of the current cross-section are instantly evaluated in the ShapeControl (SC) module and checked via set-actual comparison. This provides for real-time detection of deviations which are then converted into correction terms for the next step and forwarded to the machine control (PLC).

2.1. ShapeBase

The JCO® process control is based on a fast calculation model for dimensioning the JCO® forming process; it has been used for calculation of the process parameters since 2013. The JCO® forming process is characterized in particular by its high flexibility and the correspondingly broad production spectrum with pipe diameters from 18 to 56 inch (457 to 1422 mm) with wall thicknesses to over 45 mm. The ShapeBase software was developed for optimum adaptation of the infinitely variable parameters of the pipe forming press to the respective production. First, the software at the machine operator's request provides suggestions for basic machine settings shown in Fig. 1(a). These include the tool radius to be used, the die distance to be set and the optimum number of bending steps. Secondly, reliable starting parameters for the bending process are calculated on the basis of these machine parameters. In particular, the positions of the individual bending steps on the plate and the respective stroke of the bending tool are determined. When calculating the stroke, not only the current bending contour must be considered but in particular the spring-back after bending; this primarily depends on the wall thickness, yield point, and Young’s modulus.

Regarding the status of [4], it is also important to take the pipe closing following initial bending on a pipe forming press into consideration. During JCO® forming, the blade remains in the pipe together with the tool after the last step because the cylinders are usually designed for short strokes only. The pipe is pushed out in longitudinal direction. This means that there remains a gap of 150 to 200 mm, depending on the blade width. In pipes of small diameters with thick walls, this gap is too large for welding the edges. To enable the manufacturer to nevertheless produce pipes with these complex dimensions, a special pre-shape is formed with the help of ShapeBase which can be fully rounded from the outside by means of two targeted bending steps [5]. To this effect, two areas with an excessively large radius must be manufactured first. During closing – a free bending process –, the entire contour is brought to the set radius in two bending steps, reducing the gap to a minimum. Fig. 2 shows an example for successful closing process of an out-of-round pre-shape of 914 mm x 38.5 mm at Corinth Pipeworks (CPW) in Greece. Meanwhile, CPW has used this principle to successfully manufacture pipes of various thick-wall dimensions.

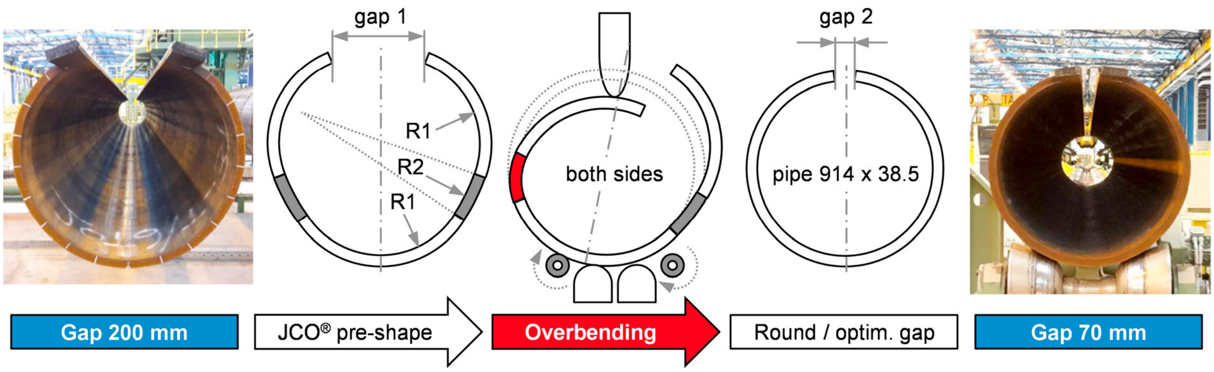

Fig 2. Pipe closing process with special pre-shape

Practice tests in a number of large-diameter pipe mills have shown that it is almost impossible to achieve a suitable pre-shape for closing thick-walled pipes using templates. Among other reasons, this is because the areas with the larger radius R2 must be placed in such a way that a collision with the opposite edge is avoided during overbending. On the other hand, the free edge must not collide with the bending blade. Furthermore, it must be ensured that an ideally-round contour will be achieved after overbending and releasing. The ShapeBase software includes respective algorithms which calculate a suitable pre-shape in dependence on dimension and number of bending steps. At the same time, the respective press parameters required for manufacturing this pre-shape are computed. These parameters can be automatically transferred to the forming press.

To achieve a specified ovality during forming, respective settings can be made analogously. This can be beneficial for the final geometry, depending on the behavior of the open seam pipe in the subsequent processes such as tack welding or expanding. At CPW, the ShapeBase program proved itself valuable in practice for the determination of process parameters for different dimensions with and without pipe closing process. It was also possible to adjust the settings for specified ovalities if these were of advantage for the subsequent process steps.

2.2. ShapeView

In the theoretical anticipation of the process parameters affecting the forming of the pipe, certain factors such as fluctuations in the yield point and wall thickness of the plate cannot be taken into consideration. Based on data of first class suppliers, the actual plate yield point for a pipe production may occasionally vary by +/- 60 MPa. Because of the resulting differences in the spring-back, the process data – above all the tool stroke – from pipe to pipe is adjusted to the current plate batch in the practical manufacturing process.

To this day, radius templates are usually used for moving in a new batch; their application is time-consuming, even for experienced operators. As explained above, this method furthermore reaches its limits when it comes to more complex pipe contours. Any fluctuations in terms of yield point and wall thickness within the plate batch would be difficult to detect, and almost impossible to compensate for manually. Furthermore, minor inaccuracies in the plate positioning can lead to deviations during forming.

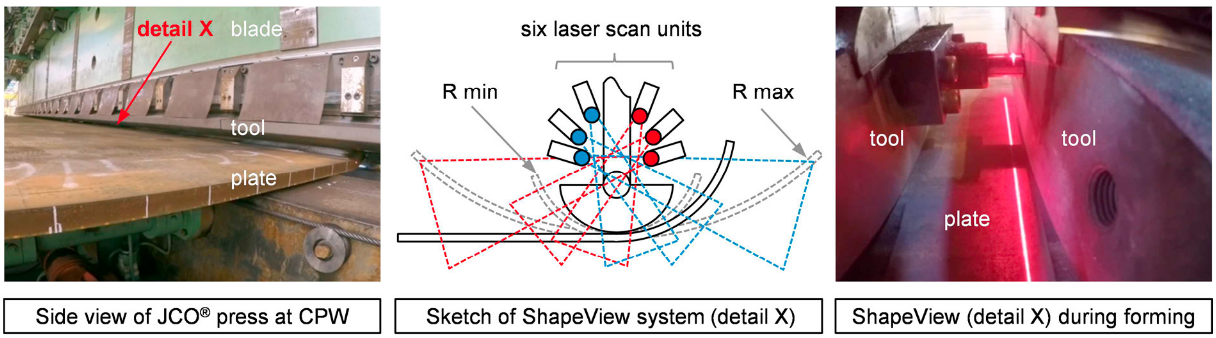

Fig. 3. ShapeView system integrated into the blade during forming

To identify such deviations in the ongoing process, the current pipe contour is captured at CPW's JCO® press in a defined cross-section for the first time after each forming step using the laser-light section sensors in the ShapeView system; see Fig. 3. This can be achieved without any process interruption or additional cycle time. Up to now, the ShapeView system is arranged in the center of the press to cover all pipe lengths.

2.3. ShapeControl

However, the system is more than just a digital template. The measured contour is compared to the theoretically expected contour. If deviations are detected, ShapeControl uses a correction algorithm. For the subsequent process step, it forwards an adapted stroke value to the PLC of the forming press. This creates a control loop of measurement and correction resulting in the optimisation of forming for every single pipe. Here, the correction algorithm must consider the current product and machine parameters, in particular diameter, wall thickness, upper tool radius and die distance. This is the precondition for the calculation of meaningful correction values. The Shape system therefore communicates constantly with the machine controller to exchange important process parameters. Equipped with its own database, the Shape system has fast access to previously calculated data records and correction approaches.

The set-actual comparison of the bent contour is particularly challenging, because the plate edges already have the set radius from the edge crimping press. For this reason, the method usually applied during V-bending, i.e.

measuring the angles at the still-straight sides after the individual bending steps [2], cannot be used here. The detection of the set-actual deviation requires an extensive contour comparison across a correspondingly large plate width. Fig. 4(a) illustrates the complex corrective approach in a simplified way. To correct the contour deviation, ShapeBase calculates resulting radial contour deviation patterns for varying stroke values in parallel with each design calculation. On this basis a correlation between radial deviation and stroke is given. By means of reverse engineering a corrected stroke value for the subsequent process step is determined for each radial deviation pattern and stored in the database (DB). During production ShapeView measures the actual contour cross section after each single forming step. Simultaneously, ShapeControl determines the current deviation pattern and identifies the corresponding pattern from the pre-calculated database. Moreover, the adequate stroke correction for the subsequent forming step is derived from the database and sent to the machine PLC. Thus, from step to step, deviations can significantly be mitigated or even compensated.

To verify the correction approach outlined above, theoretical investigations based on semi-analytical models and FEM were carried out first. Due to high accuracy in combination with short calculation times, a semi-analytical approach as described in [6] was chosen to do extensive examinations of the control algorithm.

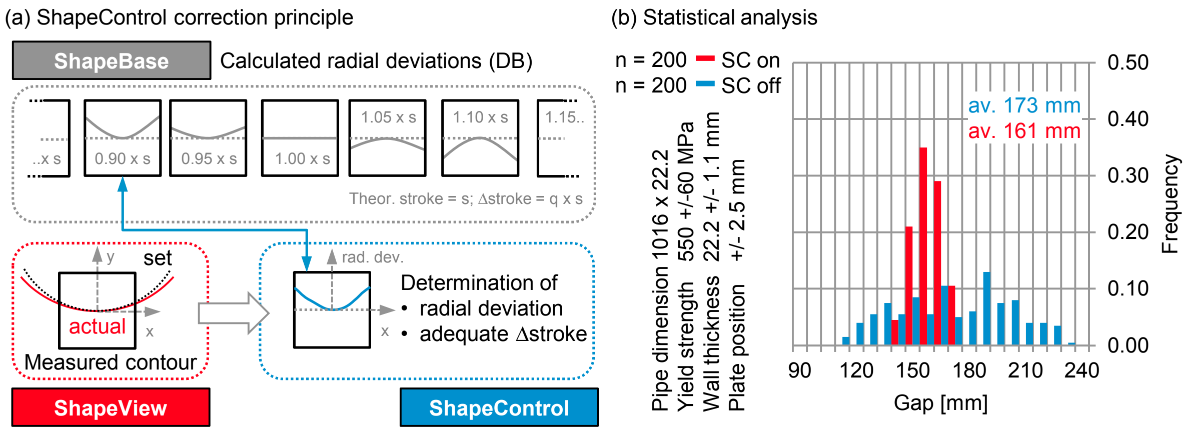

Fig 4. ShapeControl (SC) principle (a), effects of ShapeControl on gap via statistical analysis (b)

By way of example, Fig. 4(b) shows the evaluation of a Monte Carlo simulation comprising 200 calculations, which is based on the statistical variation of the parameters subject to tolerances (yield point, wall thickness, positioning). In the semi-analytical bending model, plates with random deviations in respect of these parameters were modelled. Yield point, wall thickness and positioning of the individual bending steps were varied within a defined range from one plate to the other, and also within one plate. Then, each plate was formed theoretically with and without correction of the tool stroke. The resulting gap width was used as a meaningful indicator for the compensation of the disturbances: Forming with the previously determined parameters without corrections results in heavily fluctuating gap dimensions (blue results). Determining the deviation after each step and carrying out the respective correction via ShapeControl in the next step, the desired gap width of 160 mm in the example can be achieved much more reliably (red results).

In practice, not only the contour and the gap width of the open seam pipe but especially the resulting finished pipe ovality is of interest. Thus, practical experiments have been done with regard both on gap width and final pipe ovality to verify the theoretical model and the benefits in practice.

3. Benefits in practice

As a next step, after the verification of the gap width control with the ShapeBase and ShapeControl, we had to evaluate the benefit of that on actual pipe dimensional characteristics. A production of 1016 x 22.20 mm was executed in CPW's new LSAW mill by using the two different JCO® forming approaches. In one batch 240 pipes were produced without the implementation of ShapeControl and ShapeBase and 64 pipes with the new system in full operation.

The pipe dimension which is mostly affected by the application of Shape system is the ovality. Ovality is defined as the difference between the maximum outside diameter (D_{max}) of the pipe minus the minimum outside diameter (D_{min}) when they are measured at the same plane. The results of ovality in the middle of the pipe, are presented in Fig. 5. As we can see, the pipes formed with ShapeControl presented an average ovality of 2.3 mm while the pipes without ShapeControl had an ovality of 3.3 mm.

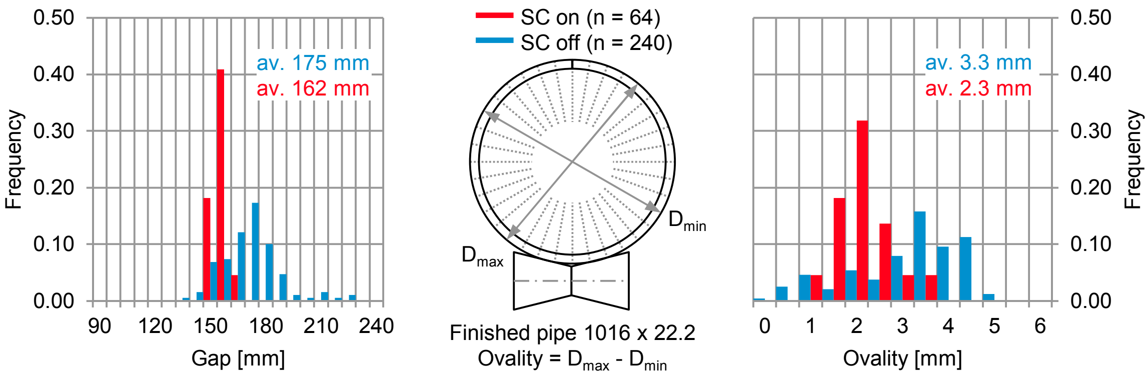

Fig 5. Benefits of ShapeControl (SC) regarding gap and final ovality in practice

4. Conclusion and outlook

In the Shape system, a reliable tool for designing and optimising the JCO® pipe forming process has been implemented. ShapeBase, the key element for calculation, is used not only for machine design but also for practice-oriented process design and optimisation during pipe production. The benefits in practice could be evidenced at CPW's when designing and producing various pipe diameters. Combined with ShapeView and ShapeControl, closed loop control of large-diameter pipe forming is possible as well. In the future, additional machines from the process chain, such as the edge crimping press, tack welding machine and expander, will be given detailed consideration in the Shape system. The control will presumably affect the pipe ends primarily.

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