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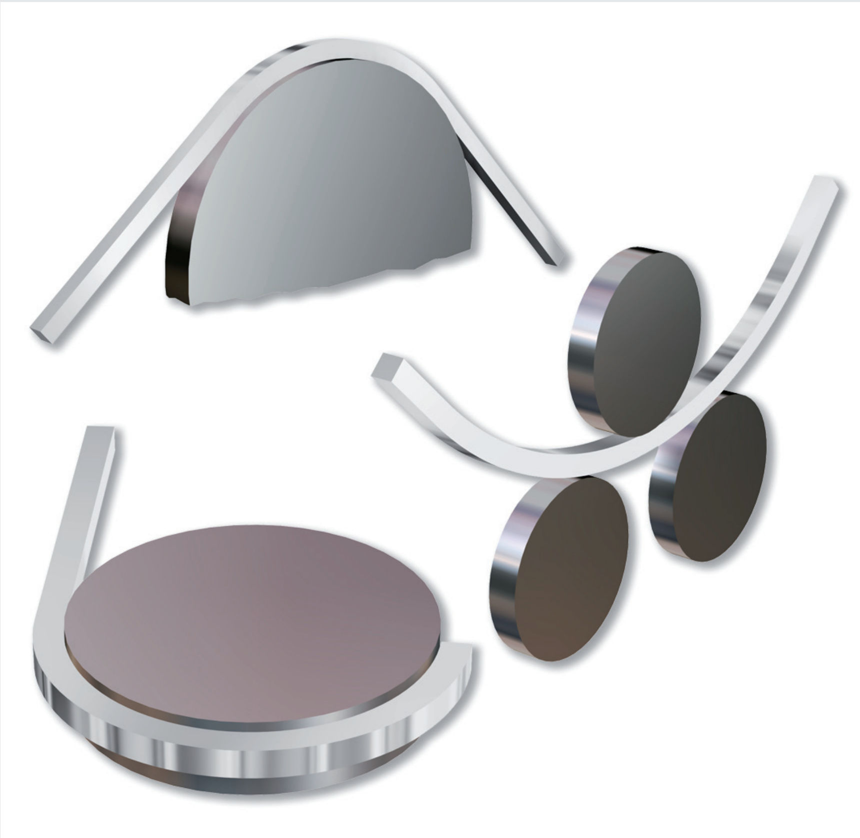
1st International Tube and Profile Bending Conference

4th DORP 2011

Dortmunder Kolloquium zum Rohr- und Profilbiegen

Dortmund, Germany
24th–25th November 2011



Institute of
Forming Technology and
Lightweight Construction

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Index

Preamble

In recent years, lightweight construction is more and more being realized by structures made of profiles with complex cross sections and high strength materials. These structures offer the advantage of high safety and good stiffness at the same time. This is an important aspect for transport systems, also providing for lowered energy consumption by the weight reduction. To realize esthetical and aerodynamic structures, there is a strong demand in industry for 3D-bend contours made of these profiles. The integration of functions and the high level of the ergonomic usage demands innovative solutions for the production technology.

The Institute of Forming Technology and Lightweight Construction (IUL) and its department of bending technology allocates a large range of solutions for these special properties by process developments, process optimization, and basic research in the field of bending and forming sheets and tubes. This aim is reached by the combination of basic research and innovative ideas.

One example is the TSS-Bending (torque – superposed – spatial) process for 3D freeform bending of profiles with arbitrary cross sections. The department has developed a machine prototype and a special process planning tool based on analytical insights. By this work the technology has reached a high industrial standard. Another example is the innovative process “Incremental Tube Forming” (ITF), a combination of spinning and bending. For this process an industrial machine prototype has been developed and a basic research project with the aim of carrying out a fundamental analysis of ITF will start in the near future. The semi-finished product sheet metal and the production of sheet metal-based profiles is also a key aspect of the department. Particularly roll forming and free bending of high strength materials and tailored blanks is under investigation. An important aim is the investigation and prevention of crack failure to allow wider process windows for the production of thin-walled lightweight profiles. For example, the process “free bending with incremental stress superposition” tries to extend these limits by the superposition of hydrostatic pressure in the bending area of the sheet metal bending process.

Not only the IUL has strong intentions to develop innovations in the special field of bending, the whole sector and many researchers face up to the future challenges. So there is a call for a forum for exchanging experiences between users, machine manufacturers, and university researchers.

In response to the great feedback in the past years, DORP 2011 is a two-day as well as international conference for the first time. In this way, there will be more room for interesting lectures, stimulating discussions, and an intense exchange of experiences and views between industry and science on an international level.

The following lectures and papers are the result of the DORP 2011 and show the excellent work of different research institutes and innovative companies. However, it cannot reflect the great interaction and fruitful discussion between our guests that the DORP conferences, organized by the Technical University of Dortmund and the IUL, are known for.

Prof. Dr.-Ing. A. Erman Tekkaya

Keynote

Tube Bending of New Generation by MOS Bending Machine

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Abstract: The bending can be used to bend tubes and suitable only for long production runs in limited sizes, not for short production runs in various sizes. Therefore the author has invented a new flexible penetration bending method and named it the MOS bending method. The bending is controlled by computer and is available for various bending radii with high precision. The bender only needs to change the easy bending program when it changes the bending radii. It does not need to replace dies. Bending radii and angles can be easily adjusted by putting a tube through the die. The new CNC bender changes the image of the conventional tube bender. The above and other benefits of MOS bending are reviewed here, together with its mechanism and characteristics of tubebending.
Keywords: metal-forming, tube forming, tube bending, CNC, MOS bending

1. INTRODUCTION

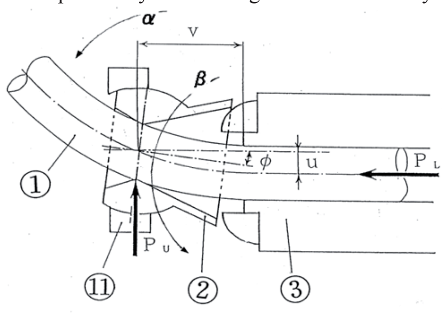
There are many kinds of tube bending methods such as press bending, stretch bending, draw bending and other various bending methods[1]- [5]. These bending methods have been developed and are used depending on operation efficiency and other requirements. Because bent circular tube products are employed to reduce production cost and weight in manufacturing many kinds of products such as fluid arrangements, furniture, transport apparatus, and mechanical parts.

A flexible bending[6] was invented by Dr. Murata and developed by Nissin Precision Machines Co.,Ltd, And it challenges the conventional image of a tube bender and is named MOS bending. The MOS bending is controlled by computer and is available for various bending radii with high precision. With this unit there is no need for replacement of dies when bending radii are changed only by a compute program change. Bending radii and angles are readily adjusted as the tube is put through a die. These and other benefits of MOS bending are reviewed here, together with its mechanism and characteristics. Some examples of the products of MOS bending are noted in this study.

2. MECHANISM OF MOS BENDING BY CNC (COMPUTER NUMERICAL CONTROL)

2.1. MOS Bending Mechanism

Figure 1 shows the principal parts of the bending machine. The mechanism is a very simple structure, with an operating sequence as follows: The relative distance between the center of the guide cylinder③ and the center of the bending die② is offset u. A tubular workpiece① penetrates the die from the guide cylinder by axial force PL, then bent as shown. For this unit, the distance (approach V) between the exit of the guide cylinder and the center of the bending die is not changed. In the neighborhood of the bending die, the tube is pushed by the bending die as indicated by the arrow.



Bending moment

$M = P_U \times V + P_L \times u$

①Tubular work piece

②Bending die

③Guide cylinder

⑪Spherical bearing

Figure 1; Principal parts of MOS bending.

The extrusion load Pu is dependent on the magnitude of the offset u. A bending moment M(=Pu×V+PL×u) operates to the bent tube. The position of the die is continuously moved by AC microcomputer-controlled servomotors. The bending die is rotated on. Angle directions as shown Fig.1 and the two angles are controlled by two AC servomotors .

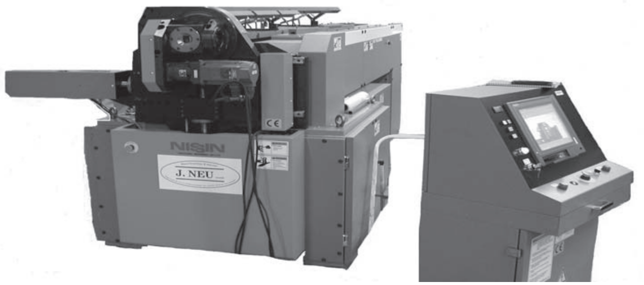


Photo 1: New CNC bender

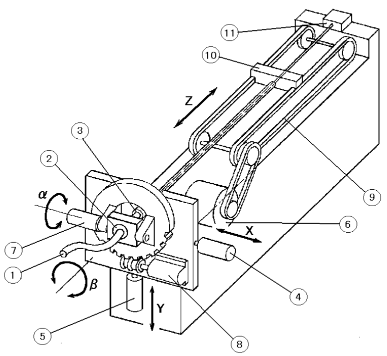
2.2 CNC Tube Bending Machine

The AC microcomputer-controlled servomotors govern the position of the bending die as shown in Figure 2. and Photo 1. Bending proceeds as follows: A tubular workpiece① is inserted into the guide cylinder③. When AC servomoter ⑥ is activated, the tube is pushed toward Z axis by plate⑩, and it is fixed to chain⑨. The tube thereby penetrates die②. The die is shifted continuously toward X and Y axes by AC servomotors ④⑤.

Once a tube is bent to a certain radius, the die is shifted to the position of offset u, which depends on the radius R. The relationship between offsets and radii is shown in Figure 4. When a tube is bent to a certain angle, the tube length is measured by rotary encoder and the tube continuously inserted into the shifted die. Bending radii can be changed at the option of the operator for three-dimensional bending. When the top of the tube is sensed by approach switch, bending commences. Figure 3 illustrates the control system of the CNC bender controlled by personal computer.

2.3 MOS CNC Bending System

The bending radius R of the tube is determined by the magnitude of offset u. As demonstrated in Figure 4, the relationship between offsets and radii is a parameter of the type of material. This relationship can be confirmed by bending experiment. Flexural rigidity, Young's modulus, and other material properties of the tube will vary with changes in material and dimensions of the workpiece. Accordingly, the bending is processed. Radius R varies even though the offset u does not change. But this unit can bend the tubular workpiece into a certain bending radius by adopting a suitable relationship between u and R for that tube, even though the tubular material or dimensions change.



①Tubular workpice ②Bending die
③Guide cylinder
④AC servomotor for control of X axis
⑤AC servomotor for control of Y axis
⑥Motor for Z axis
⑦AC servomotor for control of α angle
⑧AC servomotor for control of β angle
⑨Chain for forward of tube
⑩Plate for warding of tube
⑪Base of Mandrel

Figure 2; Main components of CNC bender.

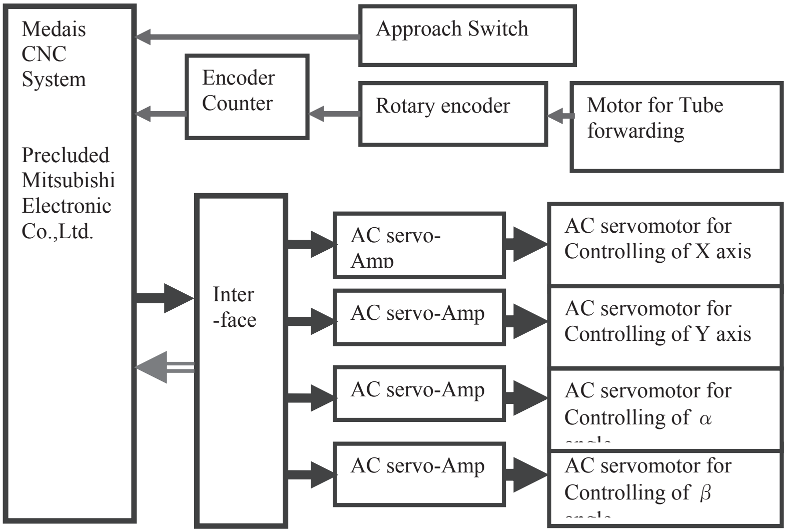


Figure 3; Control system of the bender.

The relationship between the penetration lengths of tubes Wt and the bending angle θ when the bending radii change is shown in Figure 5. Here, θ is almost proportionate to the penetration lengths of tubes Wt. But the bending radii of tubes bent by this method are, in part, not equal to the set bending radii. These sections are known as "incomplete R parts" because the tube is inserted into the die while the die is moved toward the setting position. As to software for the CNC bender, the shape of the bent tube is decided by straight parts In, bending radii Rn and bending angles θn, as shown in Figure 6.

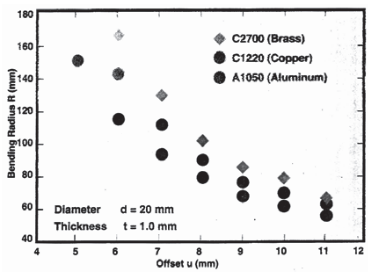


Figure 4; Relationship between offset and bending radius R.

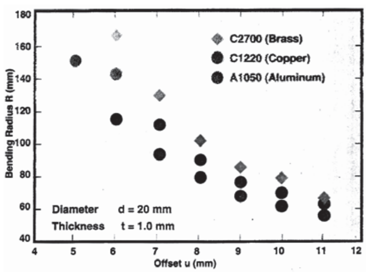


Figure 5; Relationship between penetration length of tube and bending angle.

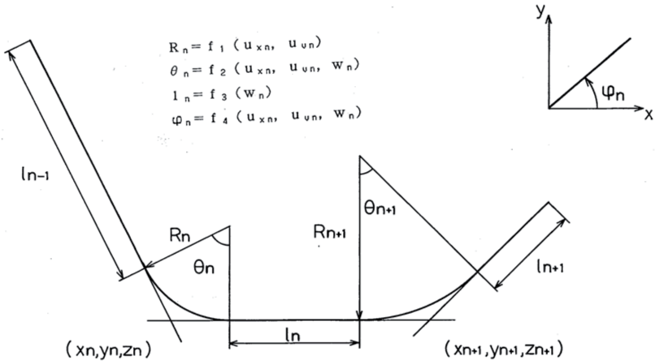


Figure 6; Control system of the bender.

The coordinate axes for the input are drawn with solid lines, and the bending direction for n-th bending is illustrated. The straight part of the tube Pn-1-Pn is overlapped upon the X axis of the input coordinate axis by revolution about point Pn-1. The n-th bending direction can be gotten by (n-1)-th bending direction. Rn, θn, In, andθn are represented by the functions given after the next equation. Therefore tubes can be bent to the required form by means of controlling uxn, uyn, and Wn - corresponding to optional Rn, θn, In, andφn.

Rn = f (uxn, uyn)
θn = f (uxn, uyn, Wn)
I n = f (Wn)
φn = f (uxn, uyn)

Where,
uxn, uyn= X axial and Y axial components of offset for the n-th bent part Wn=forwarded tube length toward Z axis for the n-th bent part. But if the material and dimensions of the tube are changed, the bending radius and the bending angle may change even if uxn, uyn, and other figures do not change. Functions on Rn andθn vary with the material and dimensions of the tube. Figure 7 is a flow chart for inputting the bending data. Cross-points of two straight parts, bending radii, and the first bending direction are input first. Then appropriate offsets and penetration lengths are calculated by computer. The equations just above, obtained from experiments, are entered into the computer.

We can bend tubes to complex shapes as shown in Photo2, Photo3 and Photo4. An outline of the bending machine movement for carrying out the bending is shown in the flow chart of Figure 7. The bending data, obtained from that program, are fed into the computer. The motor for tube formation is activated, and the tube set in the bending machine is pushed toward Z axis. When the tube is inserted into the die, the microcomputer transmits pulses to the AC servomotors to control X and Y axes. The number of pulses depends on offset magnitude. The AC servomotors are then activated and the die is shifted. During the bending recess, the penetration length of the tube is read by the rotary encoder And the die is fixed at the stipulated offset position while the necessary length of tube is inserted.

After the required tube length has been pushed out from the die, AC servomotors are again activated And the die is shifted to the next offset position for the ensuing bending operation. These procedures are repeated in regular order. After bending is completed, the motor is automatically turned off.

Photo 2

Photo 3

Photo 4

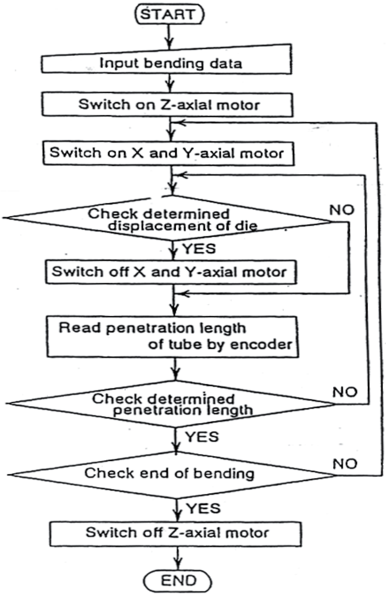


Figure 7; Flow chart of control for MOS bending.

3. CNC BENDING PROGRAM

The bending system and software are input into the computer of the MOS bending machine, enabling users to produce complex bent tube products easily, different from a conventional CNC bender. Each input bending shape is produced by means of an individual program. Figure 8 gives the six-process bending program to produce the piece shown in the Photo.5. The scheme is as follows:

```
BENDING PROGRAM

G01  L200  R40  T90  P90  F25  E25
R130  T90  P90
R40   T90  P180
R40   T90  P180
R130  T90  P90
R40   T90  P90
M02
```

GO1 = start the process
L200 = 200mm straight length
R40 = 40mn bending radius
T90 = 90-deg.Bending angle
P90 = bending direction
F,E = moving speeds of the die
MO2=end of the bending operation

Figure 8; Typical program for production of tube products by means of MOS banding.

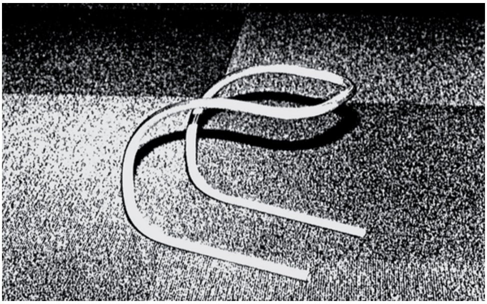


Photo 5

4. CAD AND CNC BENDING

It is difficult for us to make the program of required bent shapes of the tubes without a long time practice and excellent skill. When you design the shape of the bent tubes by CAD, the CAD data can be easily changed to the CNC bent program by a computer. Figure 9 shows the example of virtual pictures of the bent tubes on the display of CNC machine control panel at three directions coordinates. Therefore, everyone can easily check the bent tube's shapes on the display of CNC bending machine. Photo.6 is the picture of bent tube corresponding to Fig.9.

If the chairs of complex and three dimensional shapes are made by the conventional CNC bending machine, the bending process is very difficult and many kinds of complex dies are needed. Many days are required for preparing and arranging the dies and bending process. But if the new bending machine is used to make complex shaped chairs and exteriors, the CAD data is input to the computer and can be easily produced after a short bending trial.

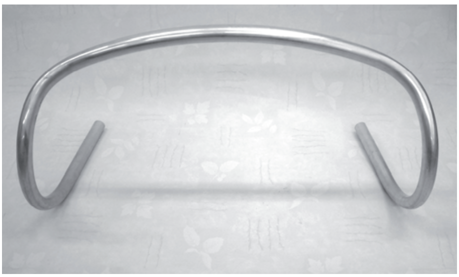


Photo 6: Sample of bent tube

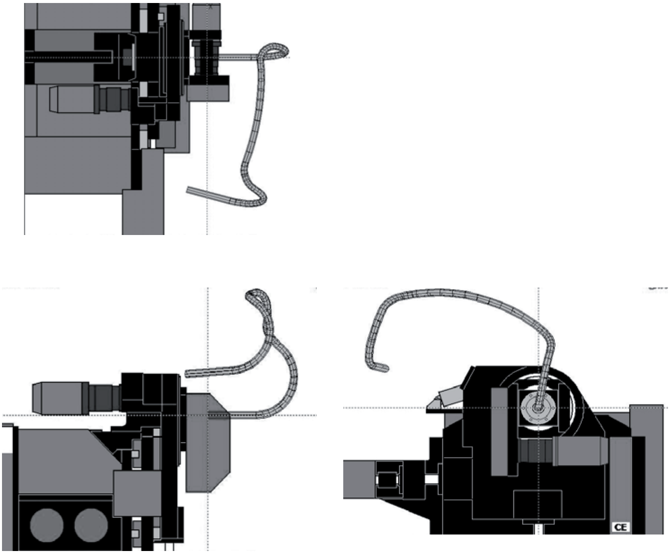


Figure 9; Virtural pictures of bent tube

5. BENEFITS OF TUBE BENDING BY MOS METHOD

There are many benefits of tube bending by MOS shown as follows.
(1) Bending radius can be easily set.
Unlike the conventional bending by pressing a tube, rolls or bending dies are not used any longer with this model so that desired radius can be specified freely.
(2) Deformation ratio of the tube cross-section is minimized.
Unlike the conventional type, the bending section is securely guided by the die so that accurate roundness can be obtained on the cross section.
(3) Bending radius can be continuously changed.
Radius and directions (X/Y) can be easily controlled by computer.
(4) Versatile bending forms are available.
Bending at an angle of more than 180degree, large-radius bending, and spiral-form bending are available now.
(5) Sophisticated bending form is obtained.
As there is no difference in levels in the bending section, a smooth and even finish can be achieved.
(6) Operability of various functions is improved.

Inputting the coordinates of bending section is also available besides ordinary inputting. Quiet environment is ensured because of motor-driven operation at high speed.

6. CONCLUSIONS

The many advantages offered by CNC bender based on the MOS method of computer control of the relative die's positions of die and tubes are being realized by users in Japan, Europe, and the United States.

The many excellent MOS-generated products include seat, exterior pieces such as monuments and buffer stops, and tubing to use in refrigerators, bicycles, and other complex designs.

By means of programs of utmost simplicity, this new generation of benders makes it available to meet needs of the most demanding and complex tube making operation.

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Session 1: Nonconventional Processes

Machine Concept for Incremental Tube Forming

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Abstract: Incremental Tube Forming (ITF) is a recently developed process to manufacture three dimensional bent tubes with variable diameter. The process principle as well as the currently used experimental setup is described. Furthermore experimental results which emphasize the advantages compared to conventional bending processes are mentioned. These results will lead to the development of a new machine for Incremental Tube Forming.
Keywords: bending, tube forming, incremental, spinning

1. INTRODUCTION

In many industrial sectors the demand of three-dimensionally bent tubes increases because of lightweight design as well as space and cost saving (Figure 1). This can be seen in the automobile and aerospace industry as well as in civil engineering, where three-dimensionally bent structures are oftentimes required [Chatti, 2005].

Figure 1: Lightweight structures [Chatti, 2005]

The aim of recently developed processes is to satisfy especially the lightweight design for structures but also to keep the stiffness constant or to increase it. This can be realized by using tubes with varying cross sections (e.g. Tailored Tubes). For example, these tubes can currently be produced with hydroforming [Koc, 2009]. To manufacture Tailored Tubes the Incremental Tube Forming (ITF) was developed [Hermes, 2009].

2. PROCESS PRINCIPLE

With ITF, bent tubes with varying cross sections can be manufactured due to the combination of a bending and a spinning process. During the process a pusher transports the tube through a sleeve to the spinning tool whereby the tool is consisting out of three spinning rolls. The spinning tool is rotating around the tube and is reducing the diameter of the tube due to the infeed of the spinning rolls. To vary the diameter of the tube, the infeed of the spinning rolls can be changed accordingly. To produce the bent tubes, a bending process is superposed to the spinning process. To realize three dimensionally bent structures, the tube can be rotated. Due to the free movability of the spinning rolls, as well as the bending head, free formed tubes regarding tube diameters as well as the bending line can be manufactured.

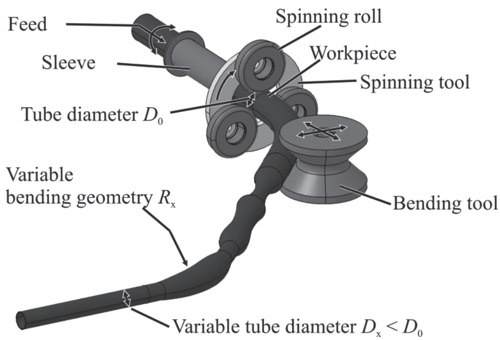
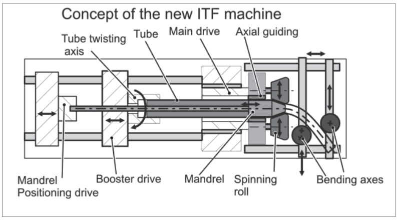


Figure 2: Process principle of ITF process

The process is currently realized on a rebuilt lathe to generate first experimental knowledge about the new process. These experiments show a great advantage of the ITF process: Due to the stress superposition of spinning and bending operation a drop in the bending forces can be measured compared to conventional bending processes. These low bending forces can be used for an improved and smarter machine layout.

3. NEW MACHINE CONCEPT

The current aim is to realize a more realistic machine system with the intent of establishing an industrial standard of the new ITF process. For this, a new machine was developed and designed. It will have eight NC-controlled axes for the different tools of the process. It will be possible to process tubes up to a diameter of 90 mm. The adjustment of the spinning system will be possible during rotation and an additional mandrel will extend the process limits significantly. In Figure 3 the design of the machine is shown [Hermes, 2011].



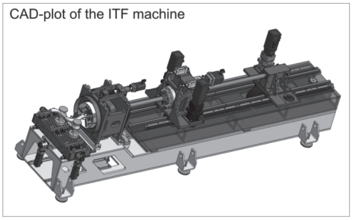


Figure 3: Machine concept and CAD-plot of new machine [Hermes, 2011]

4. CONCLUSION AND OUTLOOK

The mentioned experimental results show the potentials of the ITF process. This can be especially seen in the low bending forces which are resulting from the stress superposition of the spinning and bending operation. Based on these results a new machine with eight numerically controlled axes has been developed. This machine will enlarge the application area of the process and will exploit the maximum potential of ITF. Within the next steps further experimental as well as numerical investigations will be conducted. In addition to that an analytical approach will be developed.

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International Tube and Profile Bending Conference
4th DORP 2011
24th - 25th November 2011
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History

1903	Foundation of Gebrüder Schwarze
since 1930	Manufacture of tube bending machines (Peter Wirtz)
1953	Acquisition of Fa. Peter Wirtz, since then **Schwarze-Wirtz**
1962	First booster bender in the world developed together with VGB and Babcock and delivered to Sweden
1965	Supply of first NC controlled automatic tube bender
1996	Merger with Robitec, since then **Schwarze-Robitec**

Portrait

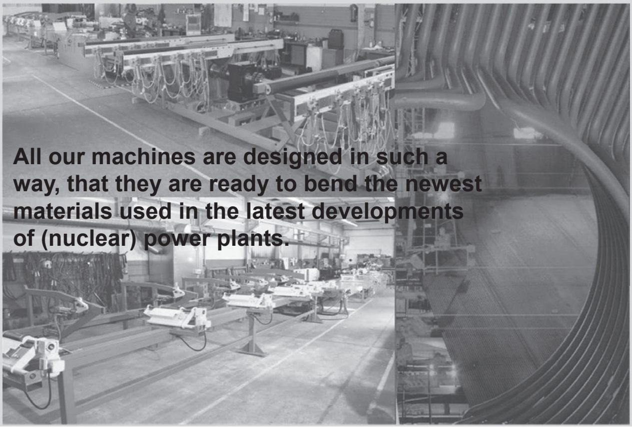
Customer orientated, qualified and motivated staff are the basis for technological advantage and quality.

Decades of experience in the manufacture and maintenance of tube & pipe cold bending machines. Continuous new development and usage of most advanced machinery is a matter of course.

Turnover 2010:	□ 20 million
Number employees:	approx. 120
Surface area:	approx. 43.000 m^2
Workshop area:	approx. 12.000 m^2


Certificate
Standard ISO 9001:2008
Certificate Holder: Schwarze-Robitec GmbH
Scope: Development, production and selling of tube and profile cold bending machines
TÜVRheinland

Our experience for your future



Booster Bending Machines

- In boiler industry people bent the products with the compression bending system with a minimum bending radius of R ~ 2 – 2.5 D.
- In 1962 Schwarze-Robitec developed on request of VGB and Babcock the first booster bending machine.
- Booster benders are suitable for cold bending of tubes without a mandrel and bending radii less than R = 2D, for tube serpentines and single bends in high strength and heat resistance steels in the same way as with thick-walled high-pressure pipes.

Advantages of the BOOSTER BENDING SYSTEM:

Manufacture of Tight Bending Radii:

Booster bending system facilities the manufacture of very tight bending radii in thick-walled tubes (OD / t ~ 10) without mandrel down to R = D within the tolerances according the former VGB Norms and the latest EN 12952-5 Norm established in 2000.

This enables the manufacture of boilers in smaller dimensions with higher capacity.

Types of machines

Model	Max. capacity at 700 N/mm² mm	Max. section modulus cm³	Min. tube OD mm	Min. / max. CLR mm
SR 60 DB	63,5 x 5	12,5	25	20 / 300
SR 80 DB	88,9 x 8	37,8	25	30 / 400
SR 100 DB	114,3 x 8,6	70,2	30	50 / 450
SR 165 DB	168,3 x 12,5	222	51	70 / 500
CNC 60 DB	63,5 x 5	12,5	25	20 / 200
CNC 80 DB	88,9 x 8	37,8	25	30 / 250
CNC 100/80 DB	88,9 x 11	46,9	30	30 / 350
CNC 100 DB	114,3 x 8,6	70,2	30	50 / 350
CNC 165 DB	168,3 x 12,5	222	51	70 / 425

Auch als TWIN lieferbar

Types of machines

Model	Max. capacity at 700 N/mm² mm	Max. section modulus cm³	Min. tube OD mm	Min. / max. CLR mm
SR 60 DB	63,5 x 5	12,5	25	20 / 300
SR 80 DB	88,9 x 8	37,8	25	30 / 400
SR 100 DB	114,3 x 8,6	70,2	30	50 / 450
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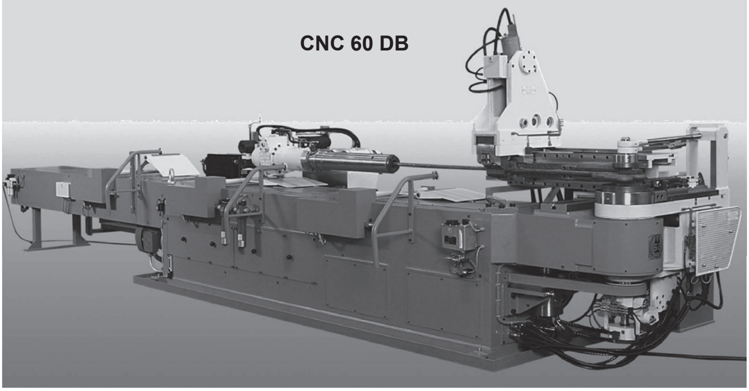
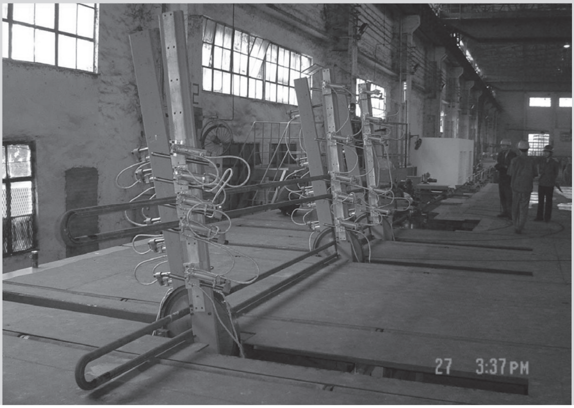
CNC 80 DB	88,9 x 8	37,8	25	30 / 250
CNC 100/80 DB	88,9 x 11	46,9	30	30 / 350
CNC 100 DB	114,3 x 8,6	70,2	30	50 / 350
CNC 165 DB	168,3 x 12,5	222	51	70 / 425

CNC 60 DB



CNC 100 - 80 DB with Flip-Over-Table



Optional:

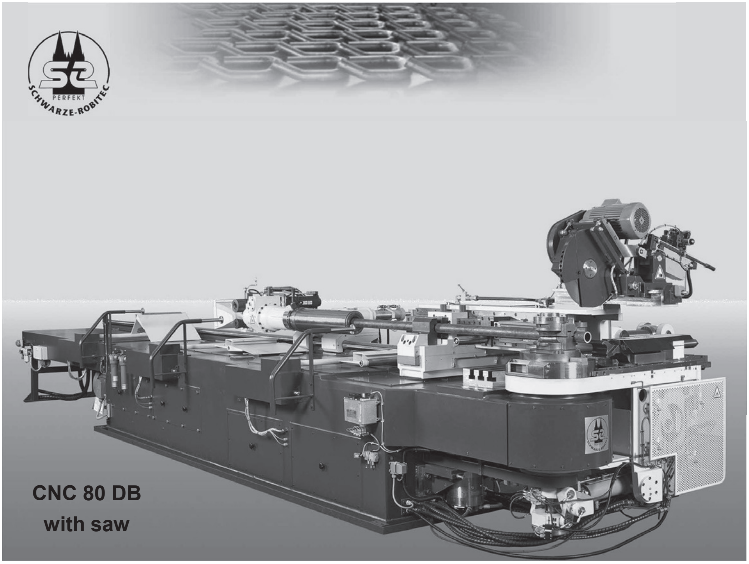
For thin walled tubes:

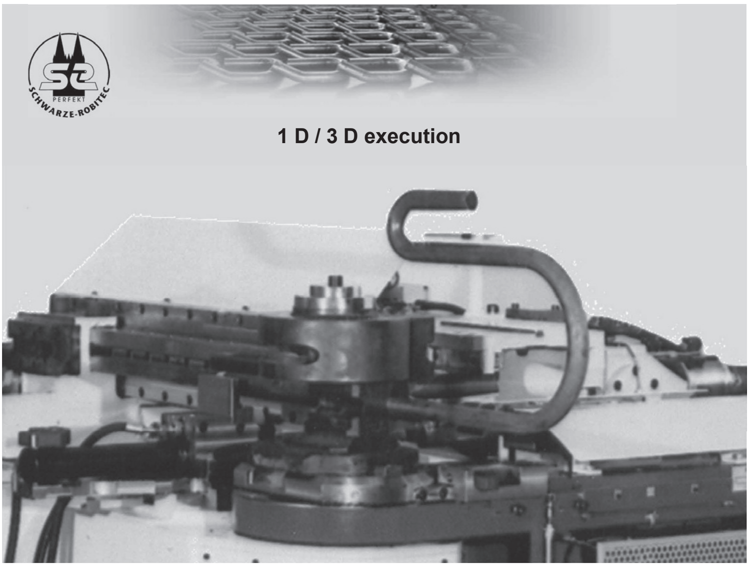
-Mandrel retraction device

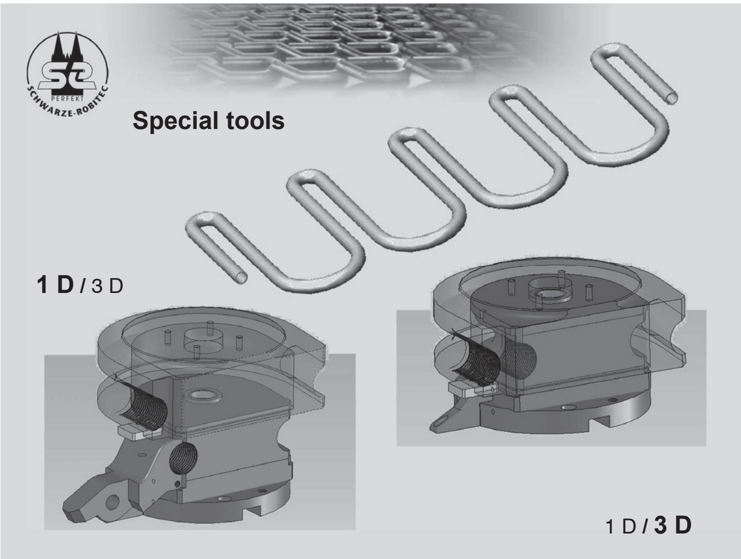
For burner openings pipes:

-Sawing device
-Bend-in-Bend device

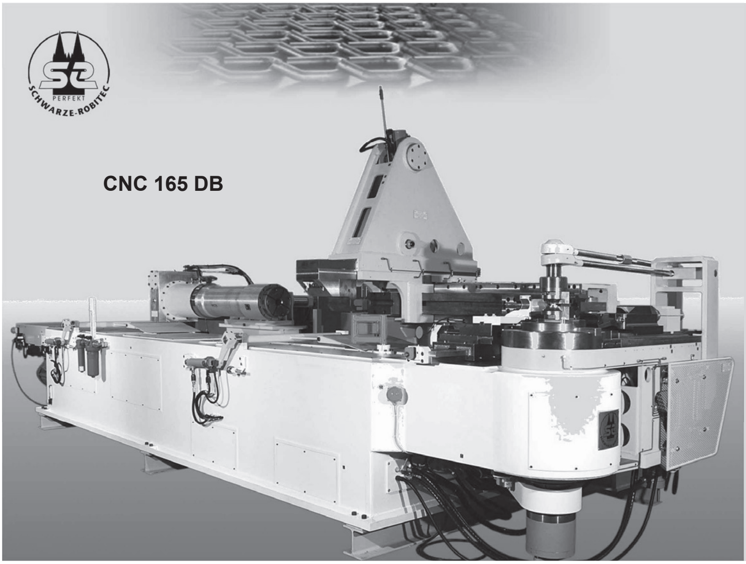
-1D / 3D device


PERFEKT
SCHWARZE-ROBITEC
CNC 80 DB
with saw


PERFEKT
SCHWARZE-ROBITEC
1 D / 3 D execution

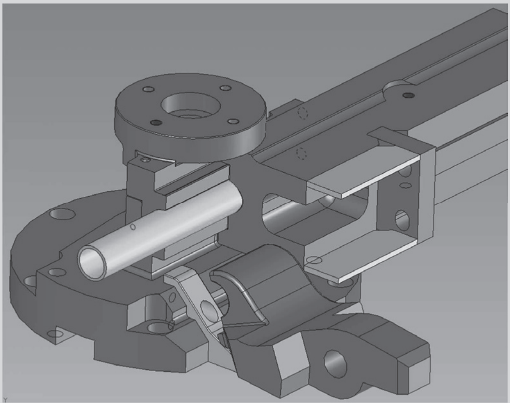

PERFEKT
SCHWARZE-ROBITEC
Special tools
1 D / 3 D
1 D / 3 D


PERFEKT
SCHWARZE-ROBITEC
For service and reparation shops
or small production units
SR 100 DB


PERFEKT
SCHWARZE-ROBITEC
CNC 165 DB


PERFEKT
SCHWARZE-ROBITEC
Tools

Tools



Bend quality and Bending Tolerances:

When bending without mandrel the booster bending system also guarantees to meet the tolerances for wall thinning and ovality according to the former V. G. B. prescriptions and the latest EN 12952-5 European Standard.

The following formula are used since 2000:

$e_{ext} = e_{act}\ (2\ r_b/d_n + 0.5)\ /\ (2\ r_b/d_n + 1)$, where

e_{ext} is the required minimum thickness at the extrados, in mm;

e_{act} is the nominal thickness of the supplied tube minus the supplier's maximum negative thickness tolerance, in mm;

r_b is the radius of the bend measured to the centre-line of the tube in mm;

d_n is the nominal outside diameter of the tube, in mm.

Bending Tolerances:

The departure from circularity of the tube bends shall be calculated from the equation:

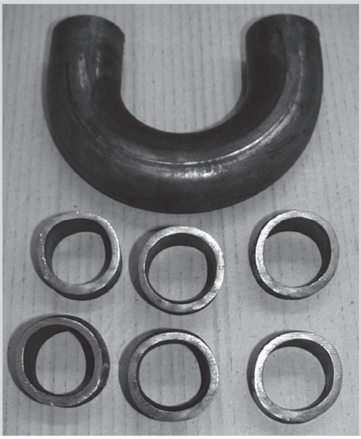
$u = 2 \times (D_o - d_o) / (D_o + d_o) \times 100\%$, where

u is the departure from circularity, in %;

D_o is the maximum outside diameter measured at the tube bend apex, in mm;

d_o is the minimum outside diameter measured at the same cross-section as D_o, in mm.

The permitted departure from circularity shall be within the limits of:
$20 / (r_b / d_n)$ with a maximum of 10% for $1 \leq (r_b / d_n) \leq 2$.



R = D

**Solutions for
large serpentines**

<u>Serpentines up to approx. 10 - 12m</u>

CNC 100 DB with Flip-Over-Table

CNC 100 DB + SR 80 DB with Flip-Over-Table

<u>Serpentines above 10 m</u>

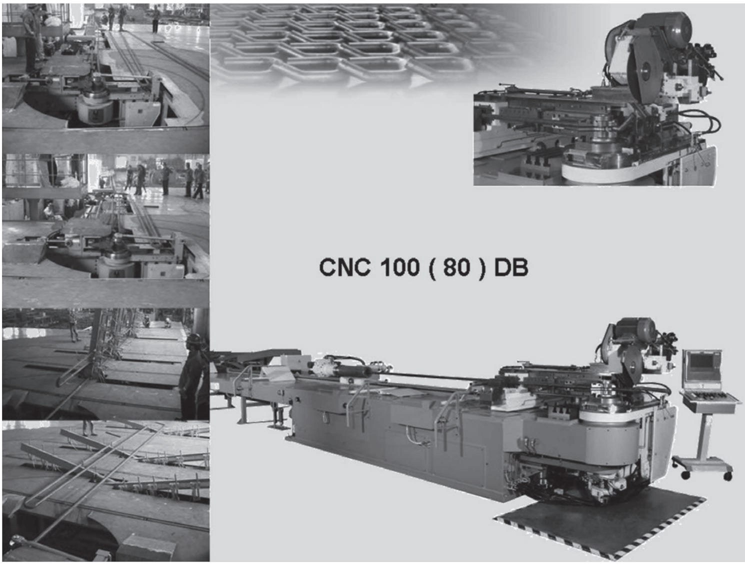
CNC 80 DB-TW with Transport Carriage

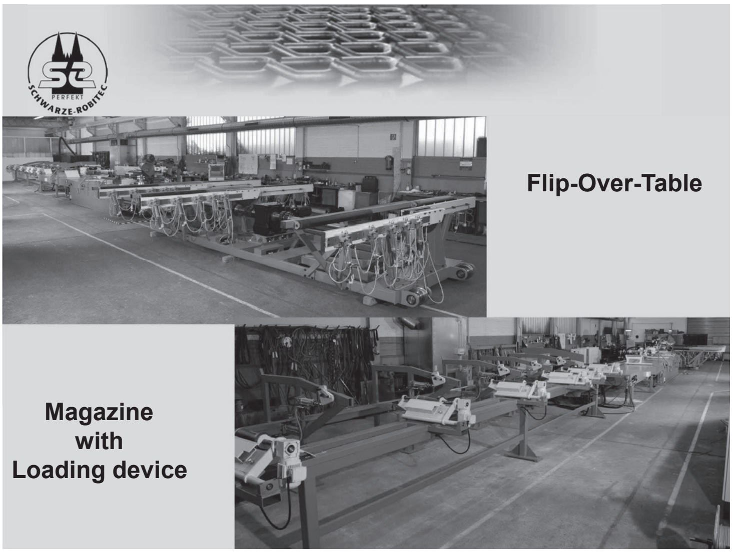
CNC 100 DB-TW with Transport Roll device

CNC 100 DB-TW-2R

CNC 100 DB-TW-IH or OB

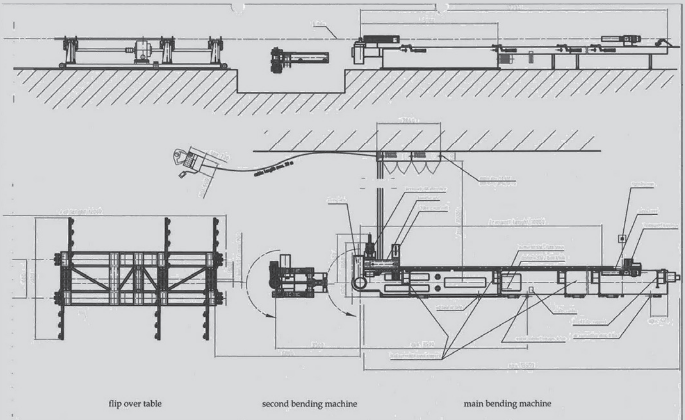
CNC 100 DB-TW-IH + OB


CNC 100 (80) DB


PERFEKT
SCHWARZE-ROBITEC
Flip-Over-Table
Magazine
with
Loading device

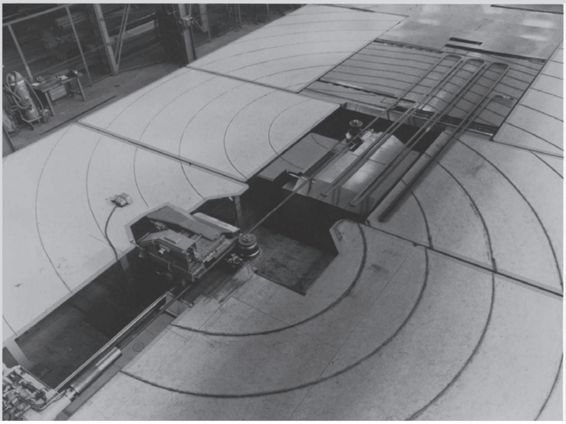
Video
Magazine with automatic loading

CNC 80 DB + SR 80 DB + Flip-Over-Table



CNC 80 DB + SR 80 DB + Flip-Over-Table

SR 80 DB on an elevator



CNC 60 DB-T

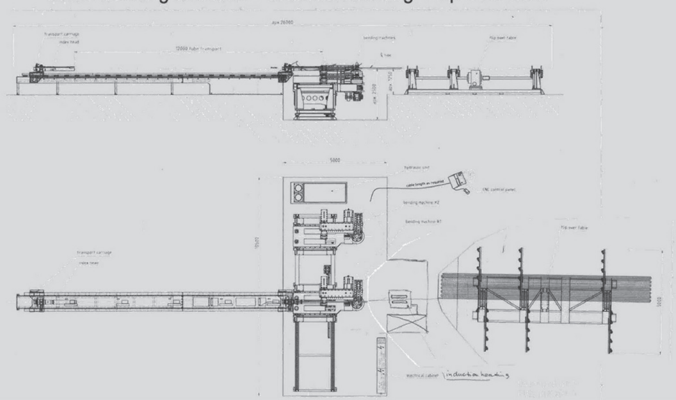
in production

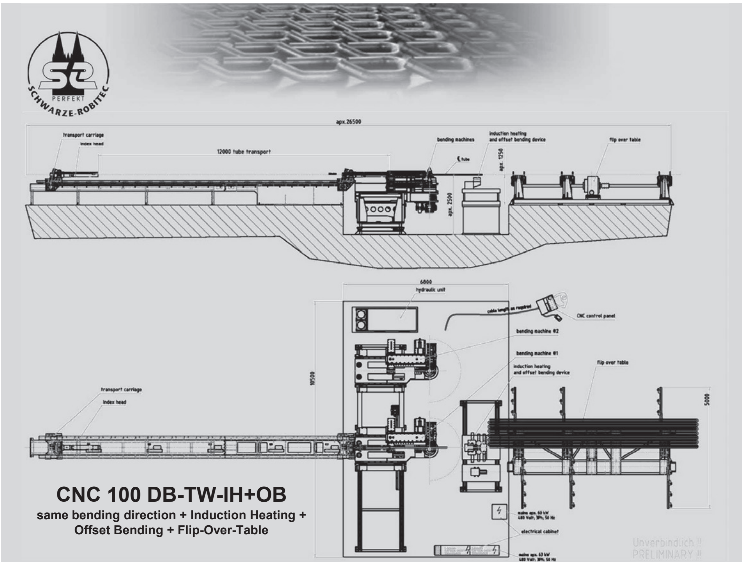
Options

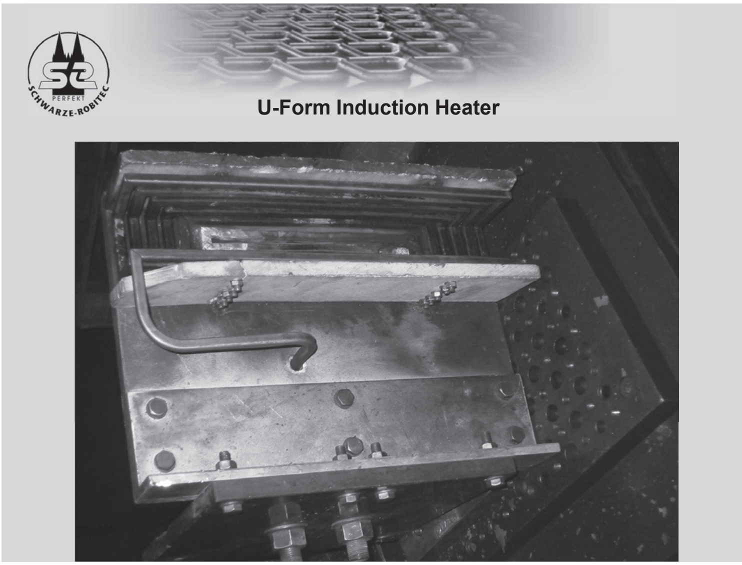
Back

CNC 100 DB-TW-IH

same bending direction + induction heating + flip-over table




PERFEKT
SCHWARZE-ROBITEC
apx.26500
transport carriage
index head
12000 tube transport
bending machines
induction heating and offset bending device
flip over table
6800
hydraulic unit
CNC control panel
bending machine #2
bending machine #1
electrical cabinet
CNC 100 DB-TW-IH+OB
same bending direction + Induction Heating +
Offset Bending + Flip-Over-Table
Unverbindlich !!
PRELIMINARY !!


PERFEKT
SCHWARZE-ROBITEC
U-Form Induction Heater

Offset Bending

Schwarze-Robitec
Membrane Tube Wall Bending Machines

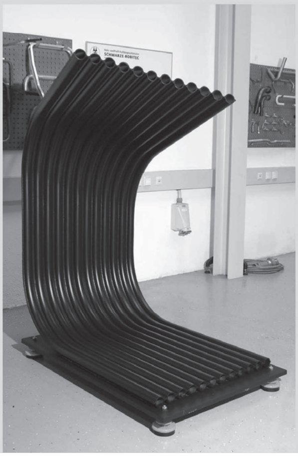
- **Our FL-machines are especially designed for bending of panels with tubes up to max. Ø 114.3 mm**
- **Machine sizes for panels with a max. width of 1000, 2000, 3000 or even 3600 mm**

SCHWARZE-ROBITEC PERFEKT

pema

Membrane wall-production

SCHWARZE-ROBITEC PERFEKT

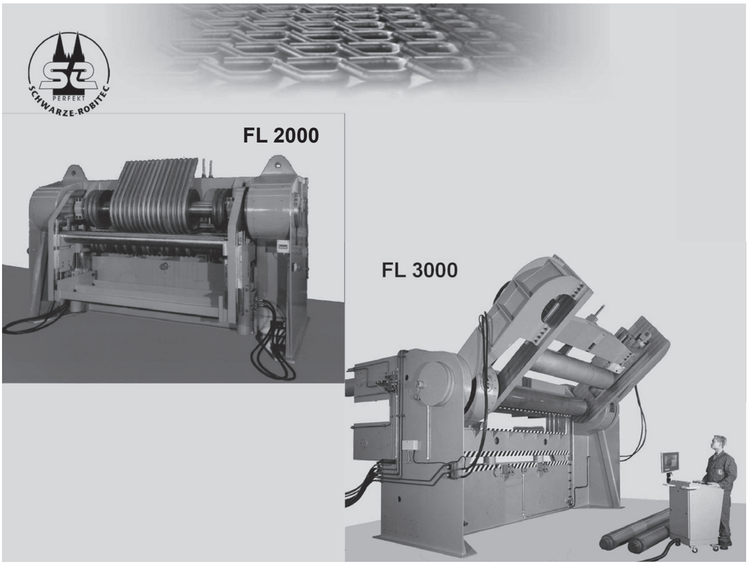


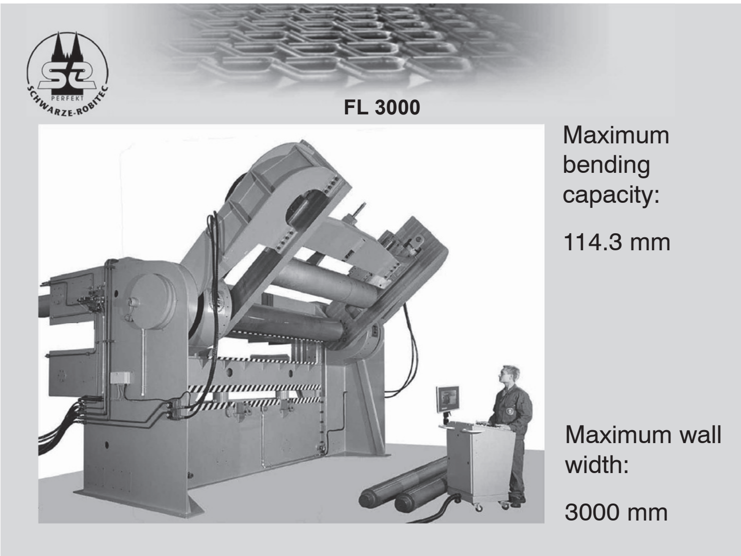
diagonal

and

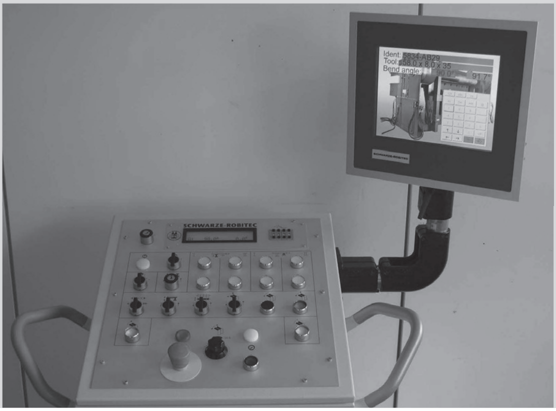
straight

bending


PERFEKT
SCHWARZE-ROBITEC
FL 2000
FL 3000


PERFEKT
SCHWARZE-ROBITEC
FL 3000
Maximum bending capacity:
114.3 mm
Maximum wall width:
3000 mm

Control FL machines



End of presentation

Session 2: Standardization in Bending Technology

VDI 3430: A Guideline for Rotary Draw Bending of Profiles

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The guideline VDI 3430 deals with definitions and descriptions for the rotary draw bending of profiles. It provides recommendations for the design of bent components and shows the process boundaries as well as attributes of the rotary draw bending process. Furthermore designations of tools and machine axes are defined. Separate chapters are dedicated to the bending tools, failure and typical influences on components during the bending process as well as the dimensioning and measuring of bent profiles. An overview of the contents of the guideline is shown in Table 1.

Table 1; Content of guideline VDI 3430

Chapter	Content	Inhalt
1	Preliminary note	Vorbemerkung
2	Process description	Verfahrensbeschreibung
3	Definitions and designations	Begriffe und Benennungen
4	Bending tools	Biegewerkzeuge
5	Semi-finished profile	Biegehalbzeug
6	Bent part and process boundaries	Biegeteil und Verfahrensgrenzen
7	Dimensioning of bent parts	Bemaßung von Biegeteilen
8	Measurement	Messen und Prüfen
9	Optimized design of bent components	Konstruktionshinweise zum „Biegegerechten Konstruieren“

The guideline was developed by a group of experts attending the “Expertenworkshop”, which is a part of the annual symposium „Biegen in Siegen“; organized by the Chair of Forming-Technology of the University of Siegen. The participants were machine manufactures, tool manufactures, profile fabricators, profile bending appliers and acadamics. Thus, the knowledge of theory and practice is combined in the group “VDI-GPL-Fachausschusses 113 – Biegetechnik”.

Another aim of this guideline is the establishment of a shared vocabulary. The communication between machine manufacturers and users as well as customers needs to be simplified. In the future, misunderstandings due to different designations can be avoided. An increase of the efficiency in production and communication is the consequence.

Therefore, the time period between design and manufacturing of products will be reduced.

With the VDI Guidelines the VDI (Verein Deutscher Ingenieure) fulfils its primary function: the transfer of technical knowledge as a service to engineers and students. Everyone may suggest a topic for a VDI guideline. If a committee is established after examination of the appropriate VDI division, it consists of honorary experts coming from all areas of research and teaching, planning and development, industry, technical surveillance and authorities. The first result of this professional exchange of experience is a draft, which is submitted to a public scrutiny. The Guideline VDI 3430 is published with the status "green paper". After examination of the comments received, the final version called "white paper" will be published. This guarantees, besides being the state of the art, neutrality with regard to individual commercial interests as well as relevance and practicability. The "white paper" is usually published as a German/English version. [VDI, 2011]

For further information please visit: www.biegeninsiegen.de.

REFERENCES

[VDI, 2011] Verein Deutscher Ingenieure e.V.: „Wissenswertes zum VDI - interesting facts about the VDI"

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Standard for tube and profile bending technology

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Abstract: Bending of tubes and profiles is gaining more and more importance in all industrial branches. The manufacturing of a bending profile requires a broad experimental knowledge. Universität Siegen, Technische Universität Dortmund and Tracto-Technik GmbH & Co. KG are working on a cross-industrial standard, which can be used equally by suppliers of semifinished products, users, and bending experts and facilitates the design of the bending part.
Keywords: Standardisation, tube bending,

1. STARTING SITUATION

Bending of profiles and tubes as construction elements is gaining more and more importance in the fields of automobiles, rail vehicles, chemical plants, materials handling, and the furniture industry, especially regarding lightweight construction. Here, it is necessary to manufacture precisely bent components, and, due to new fields of application, ever more complex shapes are called for. The selection of the bending process and the corresponding parameters for the manufacturing of the tools and the machine setting depends on numerous factors: the customers´ demands, the fields of application of the product, given tolerances, the materials as well as the economic frame conditions. As a result of the high complexity, the problem can often only be solved by trial-and-error method i.e. by cost and time intensive test production for each individual bending task. This leads to waste of time and materials, which is disadvantageous to the application of innovative bending techniques. The producers of bending components are often not familiar with the techniques, machines and tolerances. This leads to misunderstandings and, thus, needless iterative loops during the production enquiry until the appropriate design data regarding the choice of the semifinished product, the bending contour, and the bending process is achieved. Here, a cross-industrial standardization can be helpful, providing a general minimum standard for tube and profile bending parts i.e. a standardization of profile bending parts.

2. PROJECT AIM

For the first time, in this joint project, an industrial standard for profile and tube bending is developed. This serves as the specific draft which will be attached to a standardization claim at the German Standardization Institute (DIN). The claim will be submitted to the standards committee „Technical Fundamentals“with the aim to achieve a European and/or international standardization (ZEN/ISO).

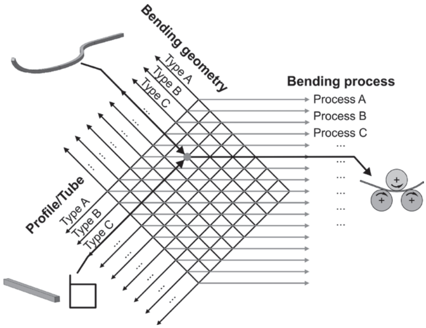

Fig. 1: Decision matrix for selecting a profile and tube bending technique.

In future, with the help of this new cross-industrial standard, it shall be possible to identify the optimal bending process for profile and tube bending parts. The bending process shall be selected considering specified demands like fields of application, materials, and economic frame conditions. In the project, these comprehensive data will be entered into a selection matrix (see Fig. 1), which will help the user make a decision by means of a convenient software tool. In addition to the basic technical parameters for the design of the individual process, a validation of the feasibility shall be provided.

Concerning the profiles, the matrix will be developed by experts from Technische Universität Dortmund, Institute of Forming Technology and Lightweight Construction (IUL) and Universität Siegen, UTS, Chair for Forming Technology. The machine and plant manufacturer Tracto-Technik GmbH & Co. KG will support the project as an expert (in the field of roll and rotational bending) regarding economic and market relevant aspects.

3. IMPLEMENTATION

The project will be implemented in several steps. First, a study will examine the standards for semifinished products and bent parts, which are partly very industry-specific, and which shall be incorporated into the new standard. For example, in the field of chemical plant building, elbows are standardized but, quite often, a corresponding bending process is not or only insufficiently specified. The second step of the project will be an examination of the capabilities of the different bending processes. For this purpose, comprehensive market studies will be carried out, which, in case of doubts, will be backed by feasibility studies and simulations and which will deliver first results regarding the design criteria for the bending process. After this, the results will be entered into a data bank, which will serve as the basis for the decision matrix and will be incorporated into the standard. At the end of the project, a decision tool will be available which can facilitate the co-operation between designers, builders, and manufacturers and, hence, help save resources in the development of bent parts from tubes and profiles. The project is scientifically based and is financially supported by the Federal Ministry of Economics and Technology (Bundesministeriums für Wirtschaft und Technologie) on the grounds of a decision by the German Bundestag (Deutscher Bundestag).

Session 3: Profile Manufacturing

An Analysis of Bend Allowance Prediction in Folding

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Abstract: The design process for bent parts includes more than the pure determination of the final cross section. It also covers the calculation of the necessary precut sheet with respect to the bend allowance. In literature, several calculation methods are known, each of them based on different assumptions or experimental work. As a consequence, considerable differences in results may be obtained. Modern CAD software usually includes miscellaneous methods in order to support the design process, but it is the engineer's task to choose the appropriate approach. This paper analyzes two common methods for the calculation of the bend allowance by comparing their results with data obtained from folding experiments.
Keywords: folding, unfolded length, bend allowance, stainless steel

1. INTRODUCTION

When designing bent parts, the determination of the final cross section is only the first step of the design process. The second step consists of the calculation of the necessary precut sheet. The unfolded length L0 is usually less than the length of the geometric middle plane, since the shift of the neutral fibre, in terms of bend allowance, has to be considered. In literature, several bend allowance calculation methods are described. Each of them is based on different assumptions or experimental work.

In Germany, DIN 6935 [DIN 6935, 2010] is widely used. It assumes that the bent part may be separated into a finite number of straight sections (a and b) and circular arcs (d) as shown in Figure 1 a). The circular arc sections are assumed to have constant radii. In Figure 1 a), ri describes the inner radius, rm is the radius of the sheet's mid plane and ru denotes the radius of the unstretched fibre, the bending angle is α and s0 stands for the sheet thickness. According to DIN 6935, the unfolded length L0 may be calculated by summing up the lengths a and b of the straight sections and the length of the circular arc d, that represents the unstretched fibre within the blank (see equation (1)).

$$L_{0\,DIN\,6935} = a + b + d \qquad \text{with } d = \frac{2\pi r_u \alpha}{360°} = \frac{2\pi(r_i + 0{,}5 k s_0)\alpha}{360°} \tag{1}$$

To define the bend allowance k in equation (1), DIN 6935 gives the following equation, limiting k between zero and one:

$$k = 0,65 + 0,5 \cdot \lg\left(\frac{r_i}{s_0}\right) \tag{2}$$

Thus, value k solely depends on the inner bending radius and the sheet's thickness. Neither material nor bending angle, or the type of bending process (i. e. press brake bending, folding, …), are taken into consideration.

In 1953, Mäkelt published on bend allowance prediction derived from experiments [Mäkelt, 1953]. In accordance to DIN 6935, Mäkelt also suggests the decomposition of the cross section into straight sections and circular arcs. To take account of the bend allowance, he draws a diagram that returns the value y, representing the shift of the unstretched fibre d (compare Figure 1 a), as a function of ri/s0. Hence, the unfolded length according to Mäkelt may be calculated with equation (3) and Figure 1 b).

$$L_{0\,Mäkelt} = a + b + \frac{2\pi\alpha}{360°}(r_i + ys_0) \tag{3}$$

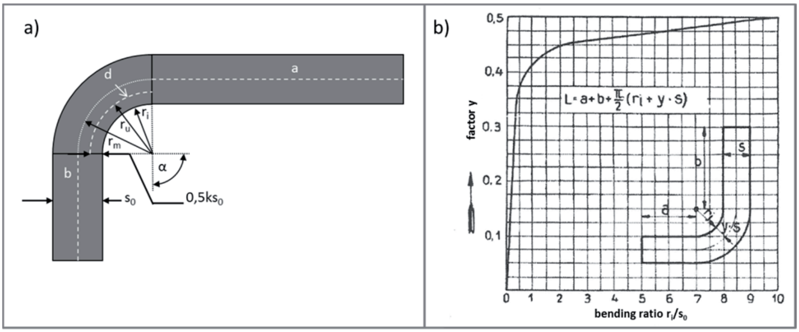

Figure 1: a) Geometry and indices of a bent part, b) Determination of bend allowance by Mäkelt [Mäkelt, 1953]

Since Mäkelt defines factor y against the whole sheet thickness, the following relationship exists between y and factor k known from DIN 6935.

k = 2y (4)

The performance of both approaches in folding is investigated within this paper.

2. EXPERIMENTS AND MEASUREMENTS

Two different materials were used for the experiments, mild deep drawing grade DD11 (Rp0.2 = 170 – 340 MPa, Rm = 440 MPa) and the stainless steel X5CRNi18-10 (Rp0.2 = 240 – 260 MPa, Rm = 750 MPa).

All experiments were conducted by folding initially flat specimen measuring 200 mm in length and 40 mm in width to a bending angle under load of 90°. The sheet thicknesses and bending radii used guaranteed r/s-values of either 1.5 or 4 for each experiment. Table I shows the materials, thicknesses and bending radii used for the experiments.

Material	DD11						X5CrNi18-10			
Thickness	2 mm		5 mm		8 mm		2 mm		5 mm	
Radius	3 mm	8 mm	7.5 mm	20 mm	12 mm	32 mm	3 mm	8 mm	7.5 mm	20 mm
r/s-Value	**1.5**	**4**	**1.5**	**4**	**1.5**	**4**	**1.5**	**4**	**1.5**	**4**

Table I: Overview of experiments

Preceding the bending operation, the unfolded length L0 of each specimen was measured. The folding operation was conducted on a servodriven press, Synchropress SWP 2500. A scematic representation of the tool is shown in figure 2 a). After the forming operation, each specimen's geometry was analyzed with a coordinate measuring machine as shown in figure 2 b).

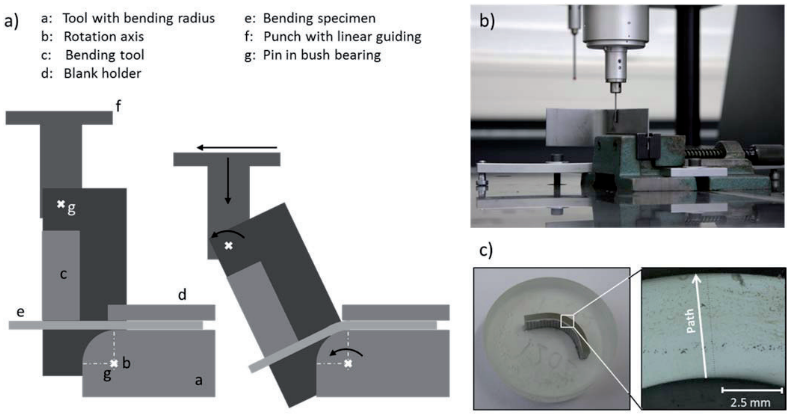

Figure 2: a) Schematic of folding tool, b) Measurement of bent specimen with coordinate measuring machine, c) Measurement of micro hardness in bending zone

The coordinate measuring machine was used to analyze the bent part's geometry. A comparison of the measured cross section with the previously determined unfolded length L0 reveals the inherent bend allowance. Furthermore, micro hardness measurements along the sheet thickness expose the minima of the work hardening within the bending zone (see figure 2 c). The location of the minimum hardness may also be regarded as an indicator of the unstreched fibre's shift.

3. COMPARISON OF RESULTS AND DISCUSSION

Figure 3 compares the k-values proposed by DIN 6935 and Mäkelt with the data obtained from folding experiments and subsequent coordinate (red dots) and micro hardness (yellow dots) measurements. First of all, good correlations of both measurement techniques were observed and analyzing the specimen by coordinate measuring machine and micro hardness leads to very similar results. The reason for the overall slightly increased ri/s0-values, compared to the initially intended ratios of 1.5 and 4, may be found in the springback behavior of the bent parts, which results in elevated ri values.

Finally, it becomes evident that all of the experimental k-values correspond better to the k-value prediction according to Mäkelt. The strong decrease in k-value for ri/s0-ratios below 2.5 as calculated by DIN 6935 cannot be confirmed. According to the presented work, it is preferable to determine the bend allowance in folding according to Mäkelt instead of applying DIN 6935.

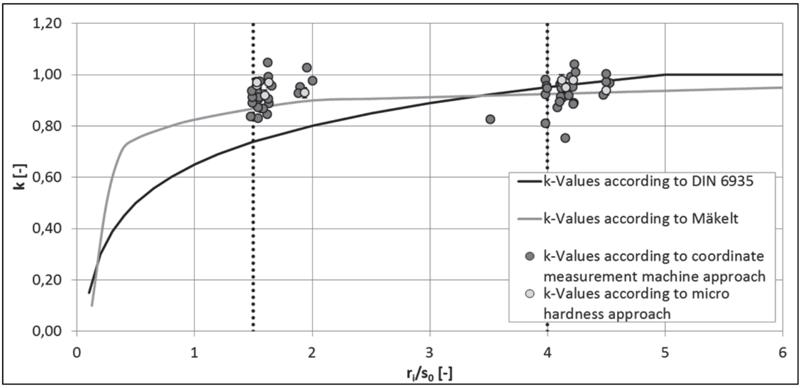

Figure 3: Comparison of k-values from experiments, DIN 6935 and Mäkelt

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data M Sheet Metal Solutions

Curvature optimized 3D-Profiles to improve the Line Speed of Flexible Roll Formed Profiles

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technische universität dortmund
4thDORP 2011
24th - 25th November 2011
Institut für Umformtechnik und Leichtbau

1st International Tube and Profile Bending Conference
4th Dortmunder Kolloquium zum Rohr- und Profilbiegen

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Overview:

- **What is 3D roll forming?**
- **History of flexible roll forming for 3D-profiles**
- **Results of some research & development projects**
- **data M's new concept to reach industrial accuracy**
- **Load optimized designs**
- **Curvature optimized contours of 3D Profiles**
- **Subsequent processes like sweeping, welding**
- **data M's offer to the industry**

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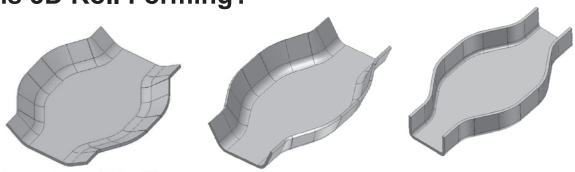
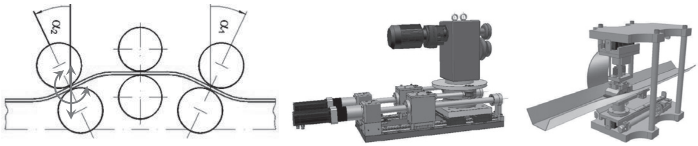
What is 3D Roll Forming?



Roll Forming of Profiles with discontinuous Cross Sections

(3D Roll Forming, Flexible Roll Forming, …)



24/25 Nov. 2011 DORP – IUL

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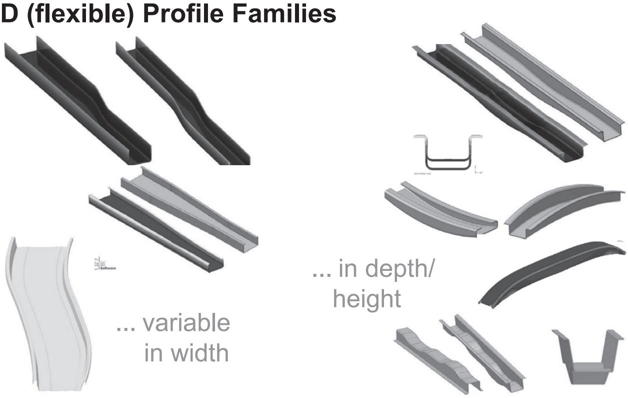
3D (flexible) Profile Families



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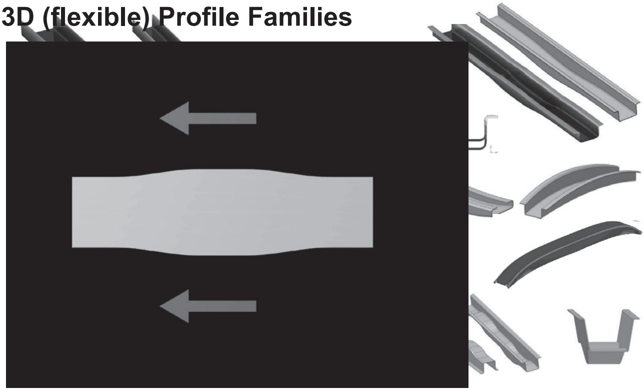
3D (flexible) Profile Families



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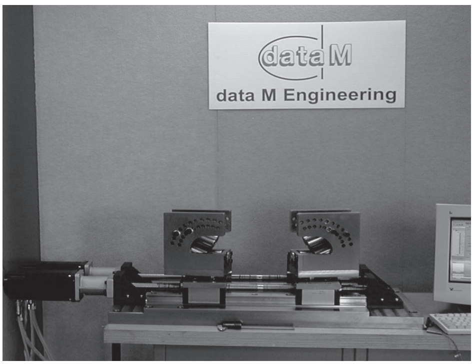
1st Generation: PtU Darmstadt (1999/ 2000)

- 1st Try-out-Line
- COPRA® AMC
  (Adaptive motion
  control) from data M
- Feasibility proven …
- But: poor accuracy



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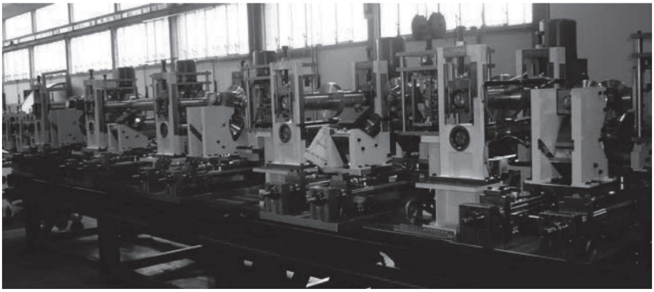
1st Generation: Integrated European Project Proform:



Flexible roll forming line for automotive parts (European R&D Project PROFORM: 2007-2010 with 23 project partners including Daimler and FIAT)

COPRA® AMC (Adaptive Motion Control) delivered by data M in 2009

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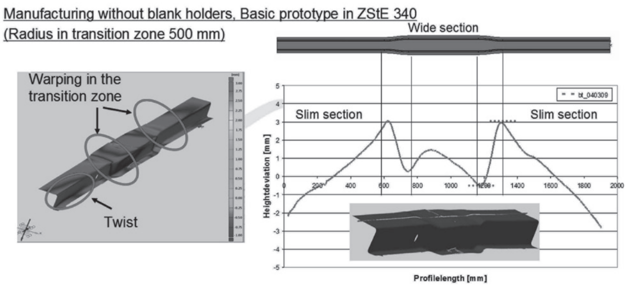
Comparison Simulation-Experiment



Warping and deviation effects on the profiles of more than 5 mm

But: feasibility - commercial, reproducability of forming has got proven

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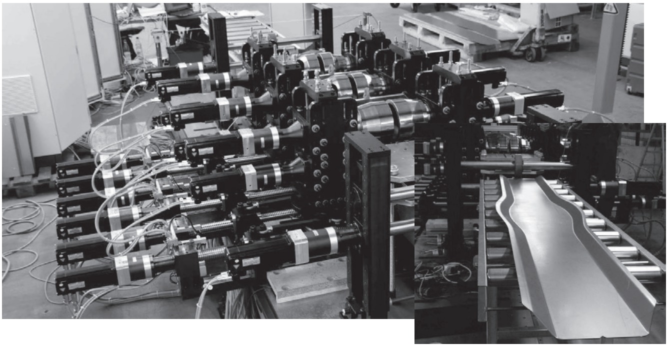
2nd Generation: data M 2010



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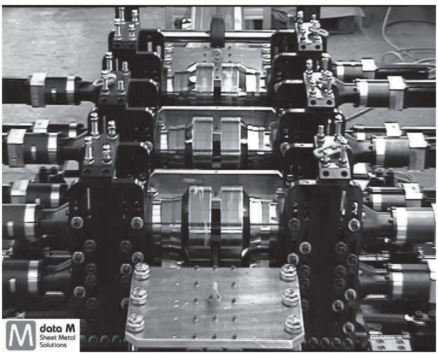
2nd Generation: data M 2010



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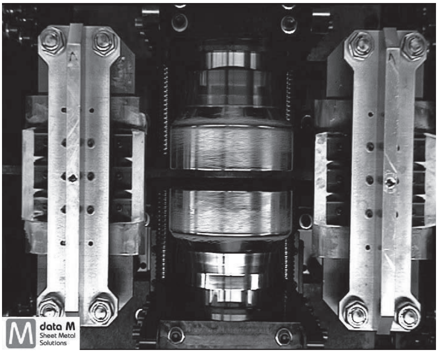
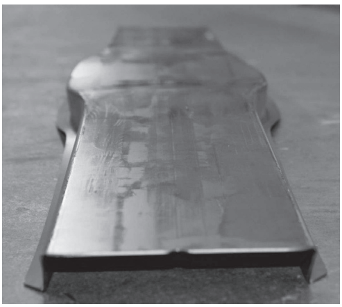
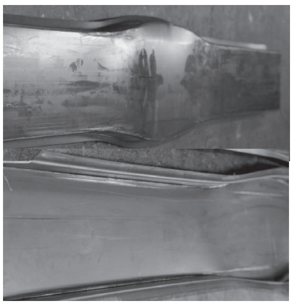
2nd Generation: data M 2010



2nd Generation: Experimental Results





Still very little warping to observe (as predicted by our FE Analaysis)
But much better than the 1st generation with an even wider spread 3D-profile.

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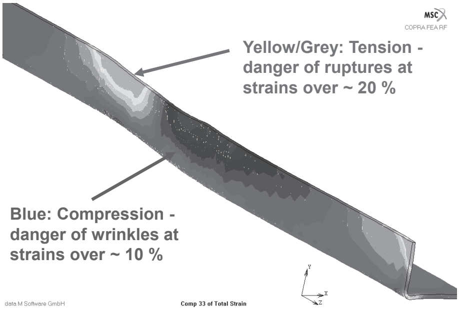
Reasons for the Warping Effects:



Tension and compression stresses in the transition areas …

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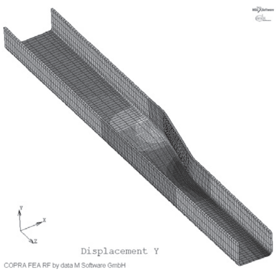
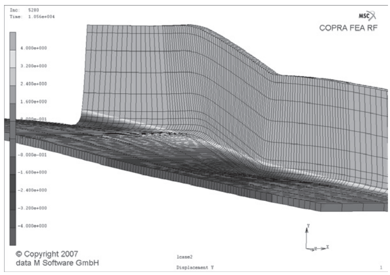
Simulation Results of Warping





… lead to warping effects - yellow and blue regions on the bottom

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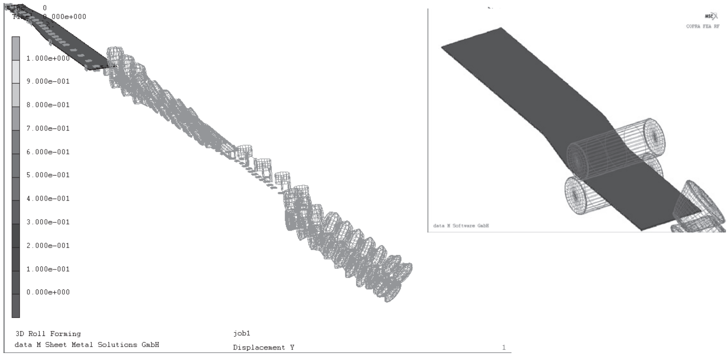
Analysis and Animation of 3D-Roll-Forming



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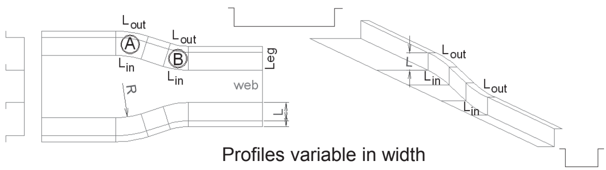
Geometrical Relations



Profiles variable in width

Geometric necessary elongation and compression in the transition zones allows rapid analytic calculation of adapted blank outline for cutting:

Strip edges stretched: **thickness and height decrease**

Strip edges compressed: **thickness and height increase**

Isotropic: height:thickness = 1:1 **Anisotropic: height:thickness ~ R-value**

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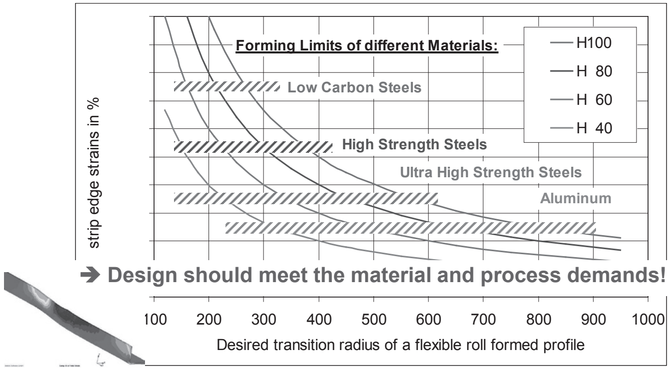
Analytical Elongation on the Strip Edges



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The 3rd Generation 3D Roll Forming Line

Achieve an industrial acceptable accuracy

Achieve high rolling speed!

Use of improved bipod-concepts and new self riding blank holder concepts

Production of 10 or 20 industrial prototypes of desired profile geometries to proof the calculated feasibility

➔ Showing the industrial acceptable parts !
Proof of this new production process !

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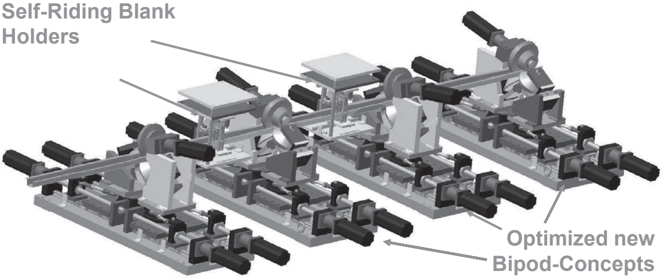
3rd Generation eD Roll Forming Line



New concepts for bipod-stands and self riding blank holder

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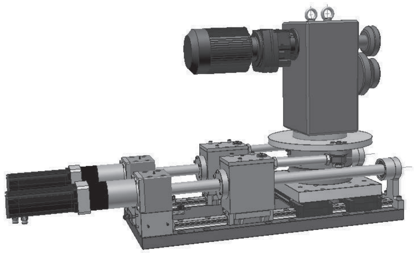
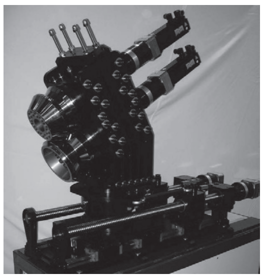
Bipod - Parallel Kinematics





data M's patented bipod-system for more flexibility and higher accuracy in flexible roll forming: presented at Tube & Wire Düsseldorf/ Germany 2010

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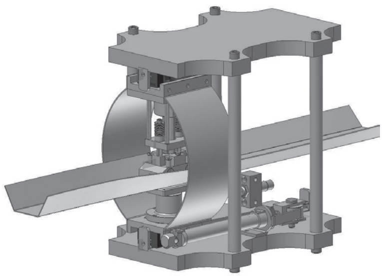
Self Riding Blank Holders



Patented self riding blank holder to better guide the sheet between the stands and avoid warping and scratching of the surface (principle sketch)

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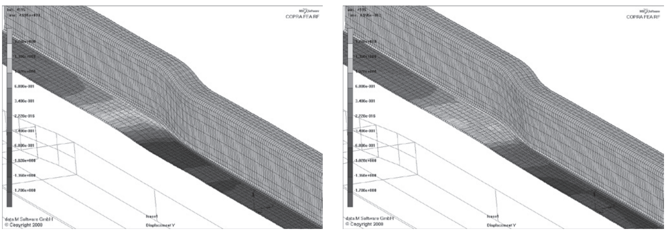
Comparison of Warping Effects



Investigation of the influence of the self riding blank holder:

Simulation shows only a fracture of warping than before - with the use of the self riding blank holder at the critical points

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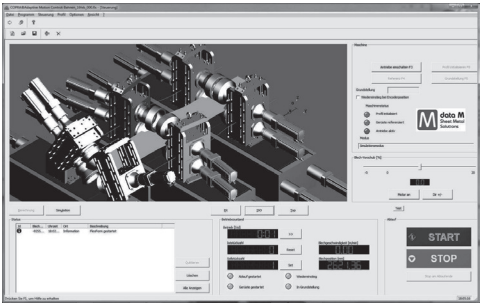
Adaptive Control: COPRA® AMC



data M‘s control software COPRA® AMC (Adaptive Motion Control) allows the precise control of up to 256 flexible axes from one PC

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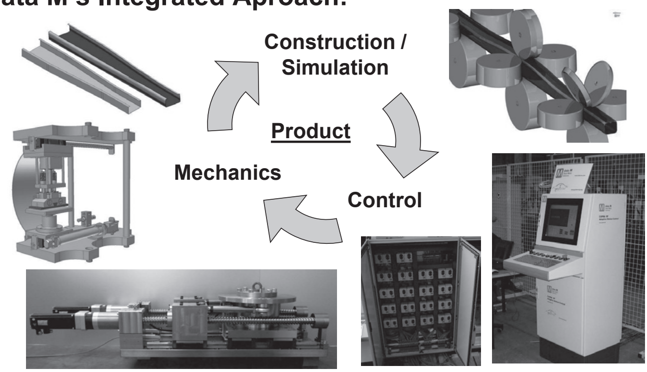
data M‘s Integrated Aproach:



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Form Light Weight Design with 3D-Steel-Profiles vs. Carbon Fibre

What about 3D-Steel-Profiles instead of CFK?

More than 3000 kg weight reduction?

But, at considerable lower prices than with CFRP?

Source: www.lightweightdesign.de

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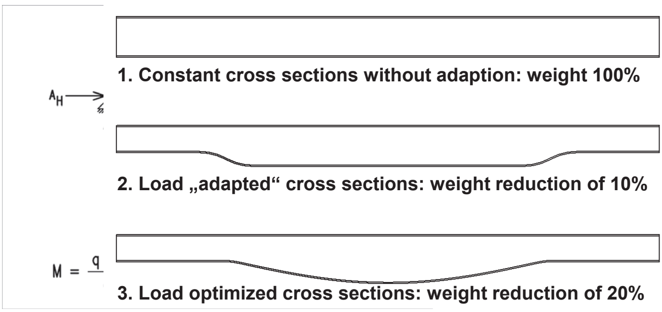
Load Adapted or Load Optimized Design



Variation 1: reducing weight by reducing beam ends: 10 – 20 %

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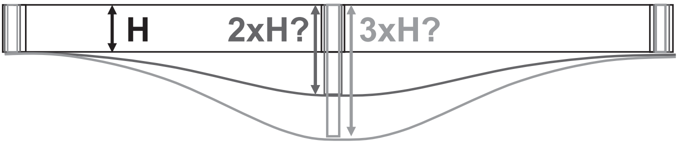
Reduction-“Potencial“ of 3D-Profiles on Truck Members



Variation 2: Higher load by higher height H in the middle of the member:

- ➔ **With double height: $I = B * H^3 / 12$ ➔ 2^3 = 8-fold load capacity!!!**
- ➔ **Or with triple height: ➔ 3^3 = 27-fold load capacity???**

Weight savings through 3D-profiles are potenciated in the 3rd Power!!!

- ➔ **either: 700% more load capacity with only 50% more weight**
- ➔ **or: 100% more load capacity with over 60% less weight !!!**

➔ **MUCH BETTER THAN CFRP AT CONSIDERABLE LOWER COSTS !!!**

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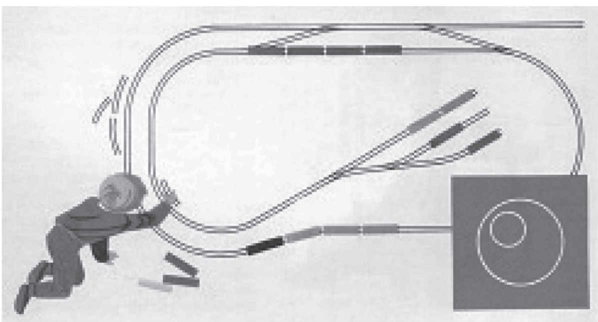

Toy Train derails at transitions from straight track to a curve

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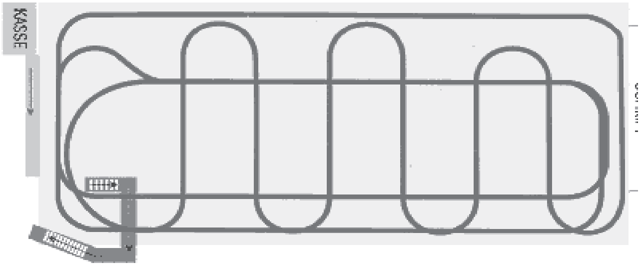
Velocity of the 'Wild Mouse'



The ‚Wild Mouse“ is a roller coaster on Munich „Octoberfest“ without smooth transitions: ➔ Speed is limited to 50 km/h

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Roller Coaster Impression on Video

„Wild Mouse“-Video:
http://www.muenchs-wildemaus.de/rundfahrt.htm

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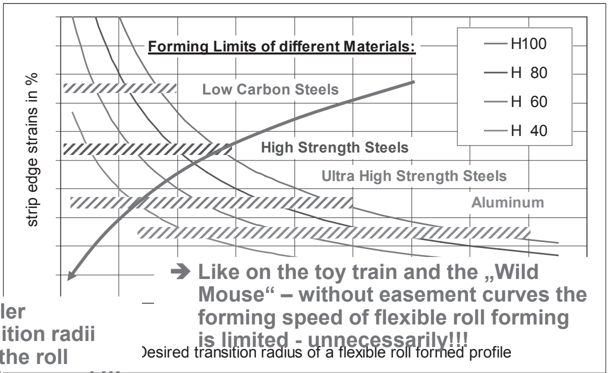
Roll Forming Speed of 3D-RF



➔ Like on the toy train and the „Wild Mouse" – without easement curves the forming speed of flexible roll forming is limited - unnecessarily!!!

➔ Smaller transition radii limit the roll forming speed !!!

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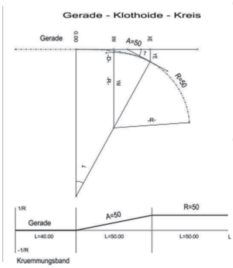
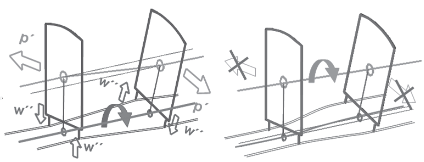
Transition Curves at Train Tracks



Main difference at the „Wiener Bogen":



Klothoide	ATM-Bogen
▪ Gerade Rampe -> Rollwinkelruck, ω´´	▪ Geschwungene Rampe -> kein Rollwinkelruck !

Klothoide and „Wiener Bogen" as transition tracks on real trains

Without such transition tracks a train would derail like the toy train!

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Formula Rossa in Abu Dhabi: max. speed: 240 km/h
➔ Optimization with curves of 5. power needed!!!

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Formula 1 video of turkish course in Istanbul:
http://www.sport.de/cms/formel-1/videos.html

Transmitting this to flexible roll forming means …

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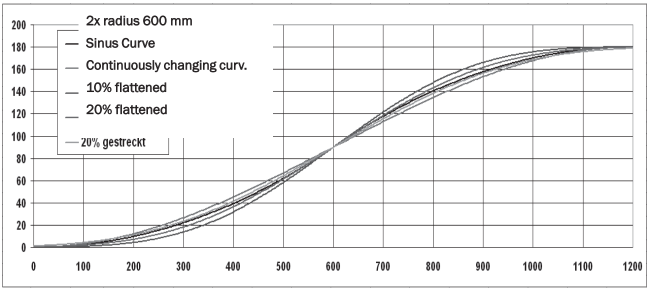
Continuously Changing Curvature



Testing of different mathematically calculated forming paths with different curvatures: What tolerances are really needed? Which forming speed can be achieved?

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Why Forming Speed Counts …

Roll Forming Speed:	**10 m / min 30ft / min**	**20 m / min 60 ft / min**	**30 m / min 90 ft / min**
1m-parts / hour:	**600**	**1.200**	**1.800**
3m-parts / hour:	**200**	**400**	**600**
1m-parts / shift:	**4.800**	**9.600**	**14.400**
1m-parts / week:	**75.000**	**150.000**	**225.000**
3m-parts / week:	**25.000**	**50.000**	**75.000**
1m-parts / month:	**300.000**	**600.000**	**900.000**
1m-parts / year:	**3.600.000**	**7.200.000**	**10.800.000**
3m-parts / year:	**1.200.000**	**2.400.000**	**3.600.000**

12m parts and longer… (36ft parts and longer…)
1.000.000

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36

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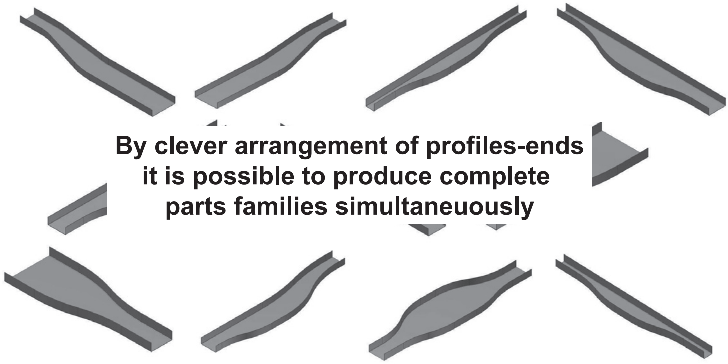
Prduct families on one line: Seven at one Blow - or 11…?



By clever arrangement of profiles-ends it is possible to produce complete parts families simultaneuously

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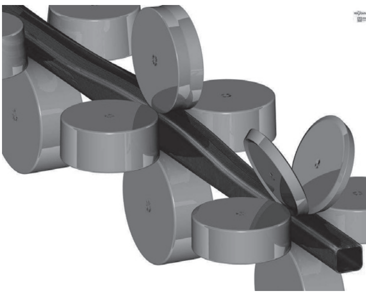
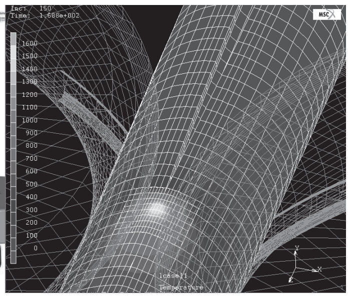
Subsequent Processes to Roll Forming:





Simulation of 3D-profiling to achieve a high accuracy of coil edges
Simulation of welding and strip thinning in order to calculate material behavior for subsequent processes like hydroforming…

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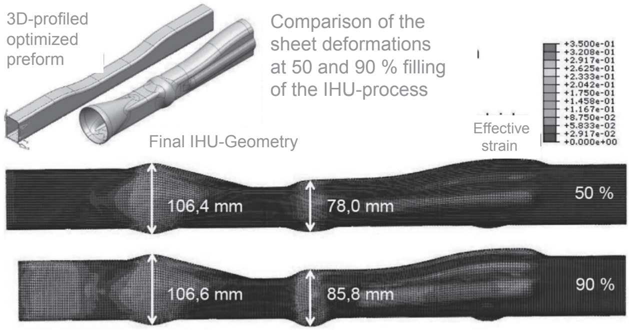
Subsequent Processes to Roll Forming:



© EFB/PtU Darmstadt

…Optimized preforms achieve higher deformation degrees on IHU

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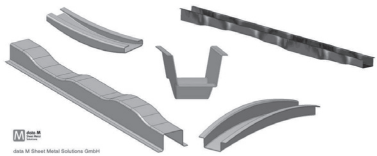
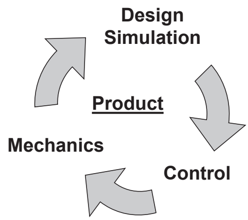
Our Offer to Industry:





Feasibility studies for this new technology
Design and production of necessary tool sets: COPRA® RF
Development of adaptive motion control: COPRA® AMC
Making of prototype parts on our own prototype mill
Detailed planning of the overall flexible roll forming line
Promoting this new technology – world wide

Many Thanks for Your Attention!

data M Sheet Metal Solutions

data M Sheet Metal Solutions GmbH I Am Marschallfeld 17 I D-83626 Valley Germany I Tel.: +49(0)8024/640-0 I Fax: +49(0)8024/640-300 e-mail: datam@datam.de I www.datam.de I www.roll-design.com

Session 4: Profile Bending

Process Limit Extension of the TSS Profile Bending Process

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**Daniel.Staupendahl@iul.tu-dortmund.de*

Abstract: Complex lightweight design in the automotive and utility vehicle industry necessitates the use of tubes and profiles made of innovative high-strength steel grades. The Torque Superposed Spatial (TSS) profile bending process is a roll based process that has the potential of continuously bending load-optimized and high-strength tubes and profiles with three-dimensional bending contours. The challenge in bending highstrength steels versus standard steel grades is the great reduction of process limits. Experimental results illustrating the advantages as well as the process limits of the bending process are presented. Finally, process extensions to increase the process limits are discussed.
Keywords: Profile; Tube; Bending; Torque Superposed Spatial (TSS); High-strength steel, Process limits

1. INTRODUCTION

In the field of tube and profile bending a steady increase in the demand of process automation and flexibility can be observed. This can be traced back to continuously decreasing batch sizes and the resulting growing model ranges, which oftentimes make high tooling costs unprofitable. At the same time, product complexity increases, meeting the current demand of unique design and light-weight construction. Kinematic and thus flexible processes for complex bending operations are for instance the Hexabend process [Neugebauer et al., 2002], the Nissin process [Murata et al., 2007], and the TKS-MEWAG process [Flehmig et al., 2006]. The general requirement of high accuracy and high process stability, however, presently is only met by the use of rotary draw bending, stretch bending [Geiger, Sprenger, 1998], or by bending and calibrating by hydroforming [Kleiner et al., 2006]. Since these processes and process chains are based on the principle of tool-bound shaping, these processes have the disadvantage of having a low flexibility, expensive tools, and high manufacturing costs when bending long profiles and large cross-sections. Resulting from the absence of an appropriate flexible procedure to bend three dimensional profiles with arbitrary cross-sections, lengths, and contours at relatively low costs the Torque Superposed Spatial (TSS) profile bending process was developed at the Institute of Forming Technology and Lightweight Construction of TU Dortmund University [Hermes, Kleiner, 2008]. Chatti et al. [Chatti et al., 2010] have shown the applicability of the TSS bending process in forming low strength steel material using S235JR steel profiles with a tensile strength of 370 MPa.

2. OBJECTIVES

To investigate the influence of bending high strength steel profiles on the current TSS bending process, process limit investigations were performed. The tested material was 40x40x2.5 mm square profile and 40x40x2.5 mm L shaped profiles made of MW1000L air hardening steel from Salzgitter Mannesmann Precision with a tensile strength of 1100 MPa. Since Salzgitter could only supply closed profiles, the L-shaped profiles were cut out of the 40x40x2.5mm square profile.

3. EXPERIMENTAL SETUP

The main parts of the TSS bending procedure are a feeding mechanism, which can be rotated (α1 axis) around its feeding axis (c-axis), and a deflecting, or bending unit, which consist of a bending matrix, movable along a linear bending axis (x-axis). The bending matrix has two compensation axes (α2- and τ-axis) to achieve a tangential run to the profile. (figure 1)

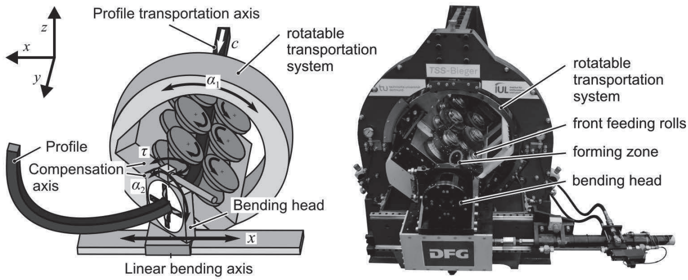

Figure 1: TSS-bending process and realized machine

4. PROCESS LIMIT INVESTIGATIONS AND EXTENSIONS

To investigate the geometric limits of bending the square profile, a contour with curvatures starting at 0.0005 mm-1 and continuously increasing to 0.0024 mm-1 was chosen. Figure 2 shows the target curvature in comparison to the actual inner and outer curvature of the profile produced by the bending test. The actual curvature after bending was measured using the 3D scanning system GOM Atos. Trails with bending curvatures above 0.0024 mm-1 directly lead to failure.

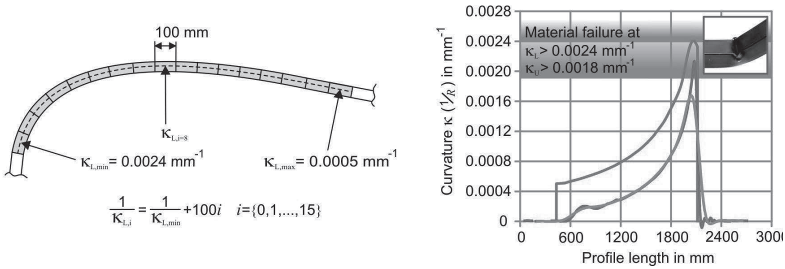

Figure 2: Target ramp curvature (κL, blue) and actual curvature (κU, inner curvature – green, outer curvature – yellow)

Additionally, the L-profiles were bent in different bending planes. Target curvatures of 0.0022 mm-1 and 0.0007 mm-1 were investigated, 0.0022 mm-1 being the maximum producible curvature. The L-profile self twisted when not being bent over its symmetrical axis, which could not be prevented with the current process setup. The self-twisting of the profile at a curvature of κL = 0.0022 mm-1 is shown in figure 3 (left).

Following these experiments, the TSS bending machine was extended by two additional servo axes that allow the numeric control of the α2- and τ-axis of the bending head. Using a systematic engineering design approach different drive concepts were evaluated and finally one ultimate design was chosen (figure 3). This new design offers the possibility to dynamically twist the profile during bending to compensate the self-twisting of unsymmetrical profiles. A compensated bending curvature of κL = 0.0022 mm-1 is shown in figure 3 (right).

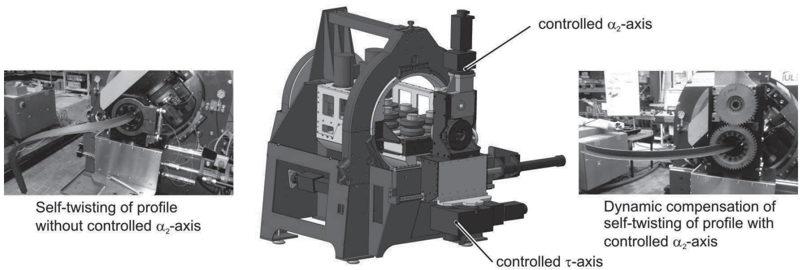

Figure 3: Extension of machine to optimize process limits

5. CONCLUSION

Process limits of bending symmetrical square profile and unsymmetrical L-profile using the TSS bending process with controlled α1 , x-, and c-axis were investigated. The investigations lead to the extension of the process by further controlled α2 and τ-axes. With this extension it was possible to compensate the self-twisting of the unsymmetrical L-profile. In further investigations, the analytic process model will be extended by the additional controlled axes. To investigate the possibility of an increase of the maximum curvature producable in bending operations, furthermore, different bending levers will be analyzed.

6. ACKNOWLEDGEMENTS

The research leading to these results has received funding from the Research Program of the Research Fund for Coal and Steel [RFSR-CT-2009-00017] and by the DFG (German Research Foundation).

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Overview

- Geometry and Rolls Positioning;
- Rolls diameter
- Profile forms and tolerances
- Profile deformation
- Measurement system for the radius
- Limits of the Measurement system

Measurement System for three roll bending of beams 2

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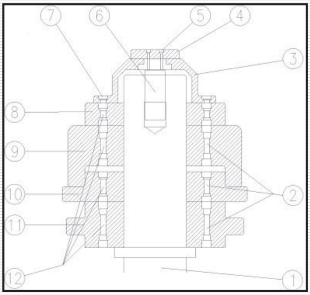
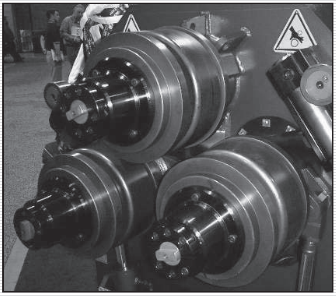
The Universal Rolls





Measurement System for three roll bending of beams 3

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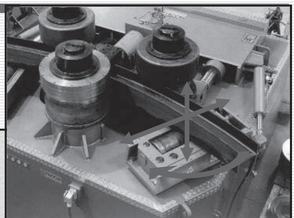
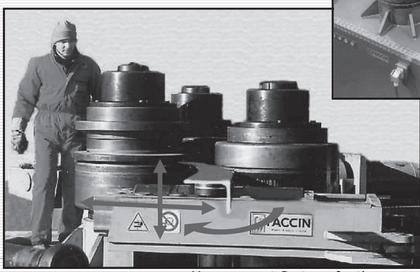
The guide rolls





Measurement System for three roll bending of beams 4

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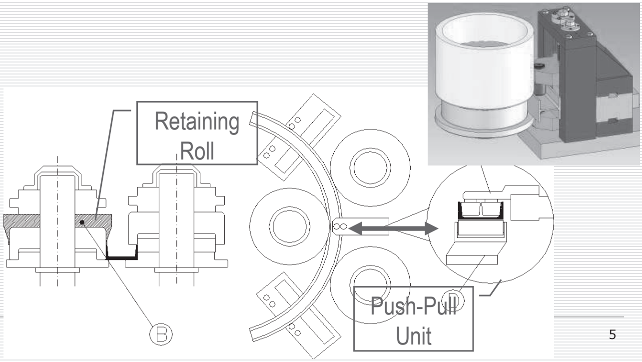
Rolling beams/channels on edge



5

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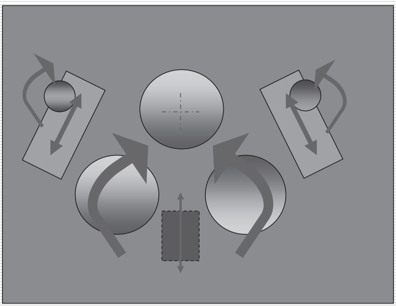
The Universal Profiles bending machine



Measurement System for three roll bending of beams

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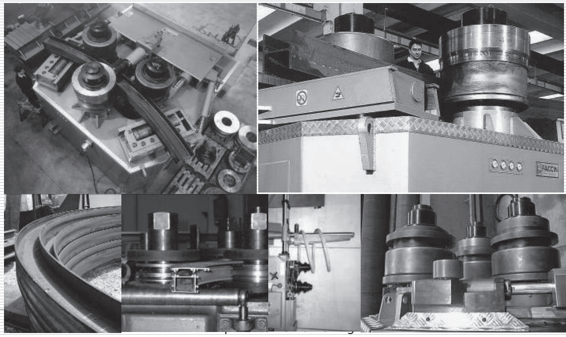
The Universal Profiles bending machine



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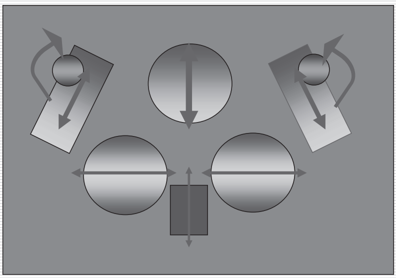
Variable Geometry Profile Bender



Measurement System for three
roll bending of beams

8

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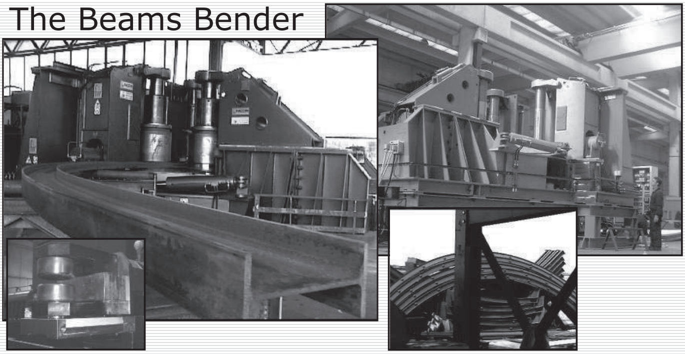
The Beams Bender



Measurement System for three roll bending of beams 9

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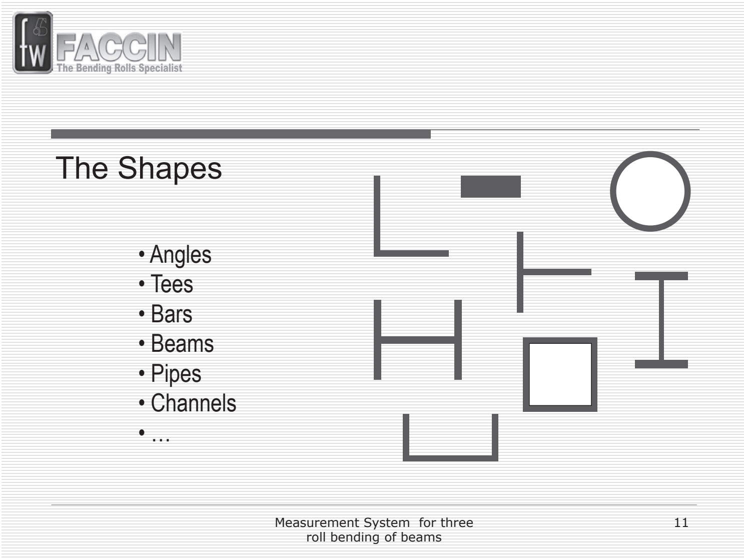
Necessary measurements for automatic bending

- ☐ Measurement of rolls diameter necessary to make a proper measurement of the radi
- ☐ Positions of the rolls defining the radius of the bended part
- ☐ The Positioning of the rolls can be measured by hydraulics up to 0,1 mm, or even smaller if necessary. Linear transducers are used.

Measurement System for three roll bending of beams 10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The Shapes
• Angles
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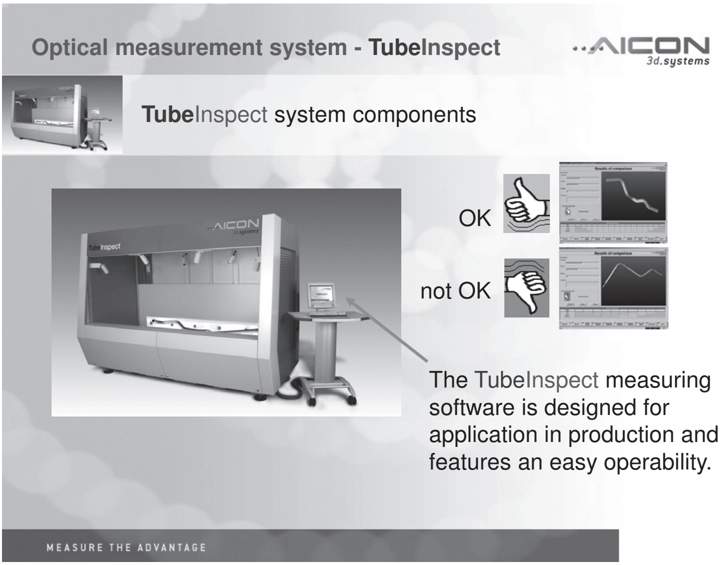
• Bars
• Beams
• Pipes
• Channels
• …
Measurement System for three roll bending of beams
11


Optical measurement system - TubeInspect
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TubeInspect system components
OK
not OK
The TubeInspect measuring software is designed for application in production and features an easy operability.
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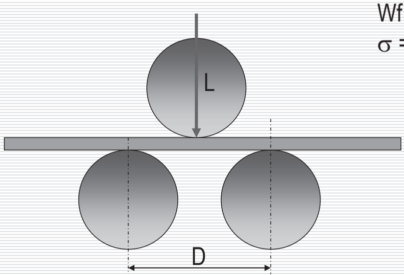
The Bending Loads



L= Load
Wf = Resistance of Section
σ = Yield Strength

$$\text{Load} = \frac{4 x W_f \times \sigma}{D}$$

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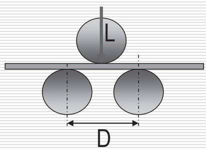
The Pressure on the profile



$$\text{Load} = \frac{W_f \times \sigma}{4 \times D}$$

1) In order to reduce the waste of material (flat end) the rolls distance has to be minimum;
2) Minimum rolls distance means higher load necessary for bending the same profile;
3) Higher load means higher compression stresses on the profile cross-section.

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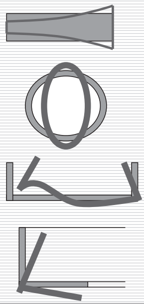
Typical cross section deformation



Thickening of bars

Ovalisation of pipes

Web deformation of beams and channels

Torsion of asymmetrical sections

Measurement System for three roll bending of beams 15

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Measurement of the radii manual

$$R = \frac{4P^2 + C^2}{8P}$$

R is the Radius
C is the length of chord
P is the depth

Measurement System for three roll bending of beams 16

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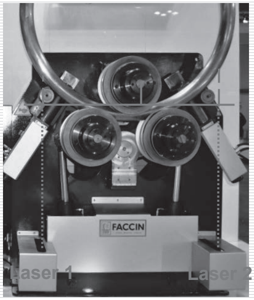
Measurement of the radii automatic

$$R = \frac{4P^2 + C^2}{8P}$$

R is the Radius
C is the distance of the Lasers (fix)
P is the depth, measured by Laser depending on rolls diameters and height of profile



Measurement System for three roll bending of beams 17

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Possible automatic cycle with Laser

Needed parameters

- desired outer diameter of the part
- outer diameter of contact rolls
- Inner height of profile
- percentage of tolerance where to stop

Bending action

- Bending rolls are positioned at the first bending point
- rotation and bending is done
- Measurement of the diameter by the laser
- calculation of new position of the bending rolls, to reach halfway the desired diameter
- These steps are repeated until the diameter is reached within the tolerances

Measurement System for three roll bending of beams 18

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Achievable results and limits

The results achieved in real customer work are
- +/-3 % tolerances on the diameter in the measurement
- Automatic bending safe until 90% of the desired diameter
- no manual measuring necessary
- no complicated calculation and measuring necessary

Limits of this system are
- The tolerances in profile dimensions
- The tolerances in material properties
- The deformation of the profile
- only suitable for big radii

Measurement System for three roll bending of beams 19

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Session 5: Measurement and Simulation Techniques

Numerical Simulation of Profile Bending Using the TSS Bending Method

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Abstract: The high demand for the realization of cost effective light weight construction, reduction of energy, and material consumption employ needs for constant development of innovative incremental, adaptive, and robust solutions capable of accurate 3D bending of tubes and profiles made from high strength steels. A kinematic bending method known as Torque Superposed Spatial – TSS Bending, capable of flexible, continuous, and adaptive 2D and 3D bending of profiles with symmetrical and asymmetrical cross-sections has been developed at the IUL – TU Dortmund. To understand the forming mechanisms of the process numerical investigations of the TSS bending method are introduced. An elastic-plastic numerical model using solid elements and high-strength steel material characteristics is presented and compared to experimental data.

Keywords: 3D Profile Bending, 2D profile bending, TSS - Torque Superposed Spatial, Numerical simulations, FEM

1. INTRODUCTION

The decrease of material, weight, and energy consumption play an important role in reaching new market demands and environmental standards. The reduction of overall weight generates an additional need for the development of high strength materials and economical solutions for robust, flexible, and cost effective forming technologies. Three-dimensionally bent tubes and profiles made of high strength materials show great potential in new design of spatial structures. The TSS bending method, developed at the IUL – TU Dortmund [1, 2], in combination with the use of high-strength materials shows great industrial potential in achieving complex continuous 3D shaped contours of profiles with symmetrical and asymmetrical cross-sections in a vast amount of applications [3]. In the following, a numerical simulation model for 2D profile bending using the TSS method is presented. The model was generated and analyzed with

Deform 3D. Results of numerical analysis were analyzed and compared with experimental data provided by the IUL, TU Dortmund.

2. THE TSS PROFILE BENDING METHOD

The TSS bending method offers a new approach to solving technological tasks and to withstand new challenges, restrictions and process limits. The system shown in Figure 1 operates in several parallel phases, which include the transportation of the profile along its longitudinal axis, the plasticization of material during bending, and the application of bending forces to realize the 2D and 3D geometry of the finished product. The continuous feed of the profile is provided by the roll based feeding mechanism, which transports the profile along the c axis. 2D bending of the profile is realized by pre-defined NC programmed movement of the bending head along the x axis. The 3D contour is then produced by rotating the torsion bearing (α1), mounted around the feeding mechanism, thereby superposing a torque, and changing the bending plane relative to the profile. The two compensation axes (α2 and τ-axis) of the bending head self-align during the process according to the movement of the profile to achieve a tangential run of the bending head

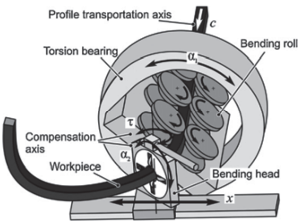

Figure 1; Working scheme for TSS profile bending process [1].

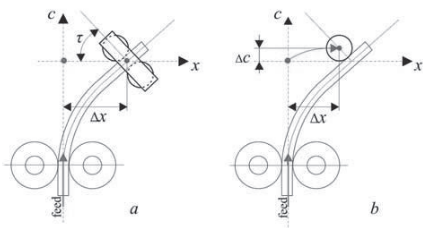

Figure 2; Comparison of the bending head position in the actual TSS bending process (a), and the position of the single roll for the 2D bending simulation (b).

relative to the profile. [1-3]

3. NUMERICAL ANALYSIS

All tools, the feeding rolls and the bending head, were defined as rigid elements within an elastic-plastic numerical model – Figure 3a. The simulation for 2D bending of square 40 x 40 x 2.5 mm profile, with an output of variable continuous bending radii ranging from Rmin = 400 mm, to Rmax = 2000 mm is shown in Figure 3b.

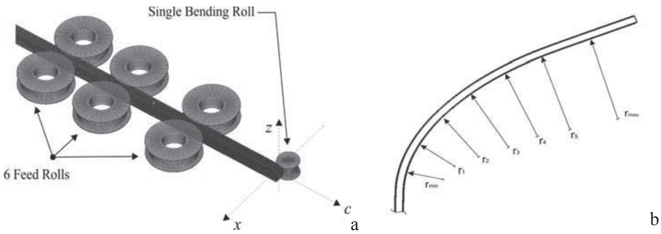

Figure 3; Input geometry model (a) – target contour (b).

The material properties assigned to the model are taken from the air hardening steel MW1000L[1]. The yield strength measures 900 MPa, while the tensile strength measures 1100 MPa [4]. The Von Mises yield function and isotropic hardening were assigned to the Lagrangian incremental type of simulation model. All loads such as the torque, bending force, and clamping force were replaced with movements. In the TSS process, the bending head constantly adapts its position with regard to the local curvature by free rotation around its vertical axis. The bending head is therefore always positioned tangential to the local profile curvature (Figure 2a). For the 2D bending simulation, the bending head was replaced by one single rigid roll, and bending movements were applied in both x and c direction as shown in Figure 2b.

4. EXPERIMENTAL ANALYSIS

The experimental analysis for the 2D bending of 40x40x2,5 mm profile made from MW1000L steel was carried out at the IUL, TU Dortmund. Experiments were done with increasing single radii, as shown in Figure 3b, from Rmin = 400 mm, in 100 mm steps to Rmax = 2000 mm. To achieve a continuous curvature were interpolated to a spline with an effective radius trend of 416 mm to 1985 mm. [3]

5. RESULTS

Optimal results for simulating 2D profile bending using the TSS bending method were gained by using the following settings: 1600 steps with a 0.1s time increment, aprox. 75.000 mesh elements. The calculation time using these settings amounted up to 42 hours. At the point where the bending head reached its final position on the x axis, maximum stress of 773 MPa (Figure 4) and a maximum strain of 0,181 were calculated. Approximately 5% of geometrical deviation was measured regarding continuality and accuracy of the profile curvature per overall length of the profile - Figure 5.

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[1] Air hardening steel, named specifically by the manufacturer Salzgitter Mannesmann Precision GmbH.

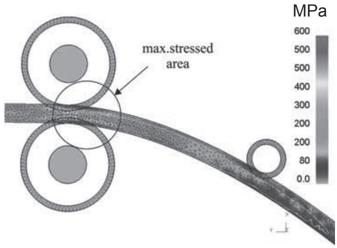

Figure 4; Detailed state of stresses within critical area.

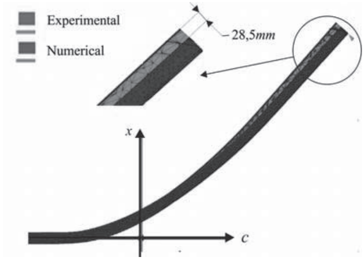

Figure 5; Comparison of the contours gained in the numerical and experimental investigations.

6. CONCLUSIONS

The numerical simulation of two-dimensional profile bending by the TSS profile bending method was introduced. Results were obtained by a numerical simulation using the Deform 3D software. Material data for the air hardening steel MW1000L was used. For the geometrical accuracy between the numerical and experimental results, a deviation 5% was measured. In further investigations, the numerical model developed will be used as a basis for detailed numerical analysis of 3D profile bending.

ACKNOWLEDGEMENT

The research was part financed by the European Union's European Social Fund, from the European Union's Research Fund for Coal and Steel (RFCS) under grant agreement n° [RFSRCT-2009-00017], and the German Research Foundation (DFG).

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[3] D. Staupendahl, C. Becker, M. Hermes, A.E. Tekkaya, M. Kleiner, New methods for manufacturing 3D-bent lightweight structures, In: Proceedings of the 3rd International Conference on Steel in Cars and Trucks, 2011 S. 120-129.
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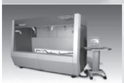

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Measurement of bent parts for the correction of bending machines

Dr.-Ing. Christoph Dold

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Topics

- Company profile: AICON 3D Systems GmbH
- Optical measurement system TubeInspect
- Measurement of bent parts
  - Inspection of roll-bended parts
  - Inspection of free-form bended parts
  - Contour inspection
- Process control with TubeInspect
- Summary

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AICON 3D Systems GmbH – company profile

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AICON Company Profile

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AICON History

- Founded in 1990 in Braunschweig, Germany, by Carl-Thomas Schneider and Werner Bösemann
- Spin-Off from Volkswagen R&D and Braunschweig's Technical University
- Located in Northern Germany near Hanover and Wolfsburg
- Easy to reach by train and air (40 minutes to Hanover Airport)

ISO 9001:2008 DNV Certified Company

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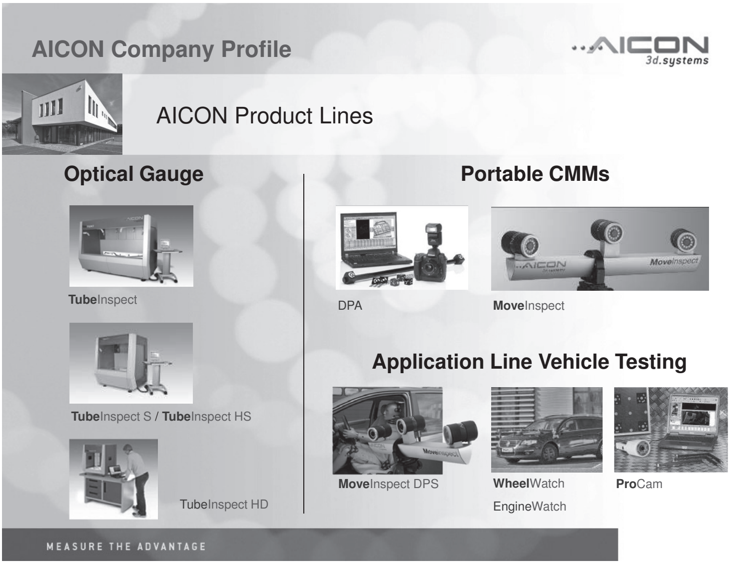
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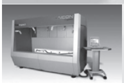

History of tube measurement at AICON

1994:
First installation at an automobile manufacturer

2011:
- More than 140 installations world wide in all tube manufacturing sections
- Continuous software development

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TubeInspect is dedicated to ...

... programmable optical gauging

... setting up and correcting bending programs

... digitizing of master tubes for Reverse Engineering

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Optical measurement system - TubeInspect

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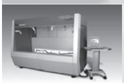
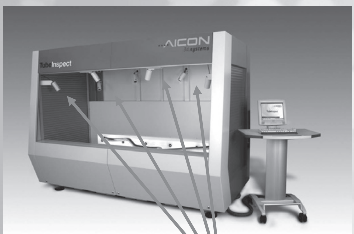


TubeInspect system components



High resolution digital cameras acquire the tube details.

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TubeInspect system components

The transillumination assures equal conditions of brightness.

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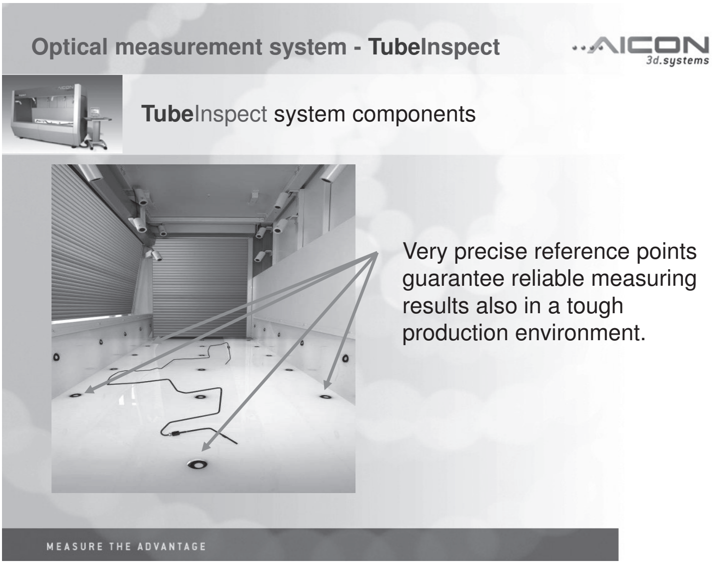
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Very precise reference points guarantee reliable measuring results also in a tough production environment.
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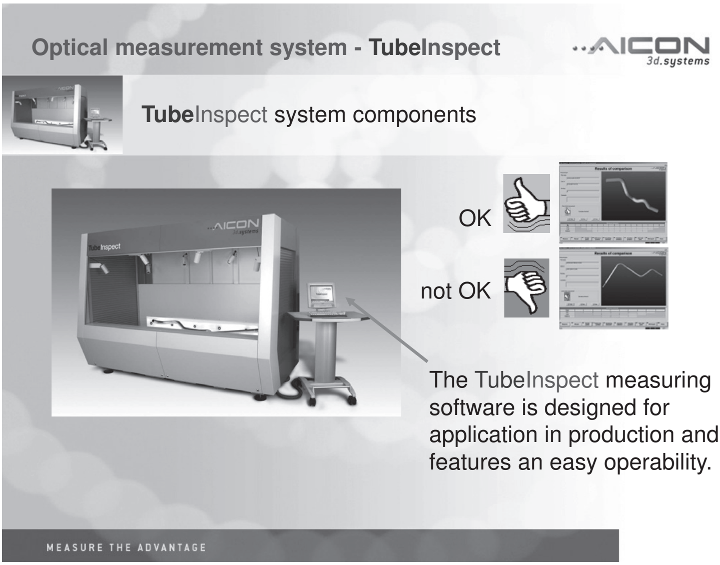
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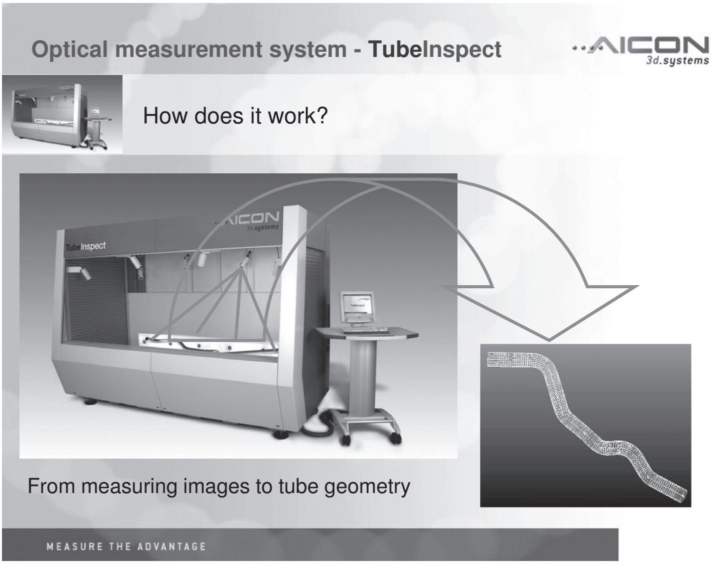
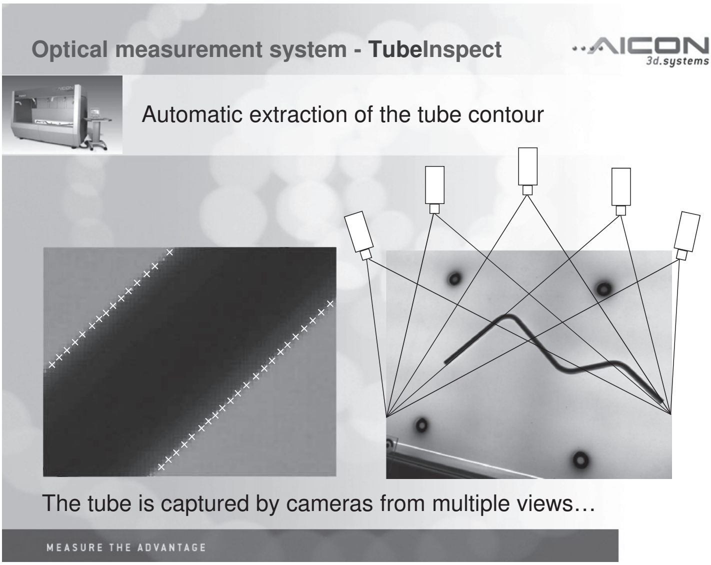
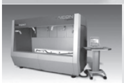
not OK
The TubeInspect measuring software is designed for application in production and features an easy operability.
MEASURE THE ADVANTAGE

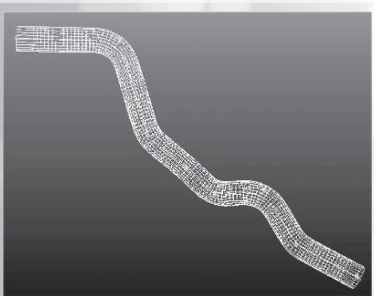

Optical measurement system - TubeInspect
AICON 3d.systems
How does it work?
TubeInspect
From measuring images to tube geometry
MEASURE THE ADVANTAGE


Optical measurement system - TubeInspect
AICON 3d.systems
Automatic extraction of the tube contour
The tube is captured by cameras from multiple views…
MEASURE THE ADVANTAGE

Optical measurement system - TubeInspect



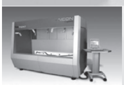
Automatic extraction of the tube contour



... and a 3D cylinder model is generated.

MEASURE THE ADVANTAGE

Optical measurement system - TubeInspect



Technical data for different models

	Model	Measuring volume [mm]	Maximum measurable tube lengths	Measurable tube diameters	Accuracy
	**Tube**Inspect	2.500 x 1.100 x 700	5 – 7m	3,2 – 200mm	± 0.1mm
	**Tube**Inspect S	1.100 x 1.100 x 700	1-2m	3,2 – 200mm	± 0.1mm
	**Tube**Inspect HS	1.080 x 980 x 500	1.5m	2 – 100mm	± 0.050mm
	**Tube**Inspect HD	450 x 400 x 200	0.6m	1 – 20mm	± 0.025mm

MEASURE THE ADVANTAGE

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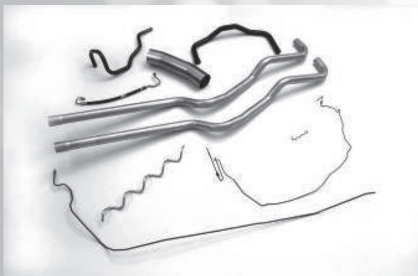
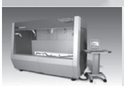
Measurement of bent parts



MEASURE THE ADVANTAGE

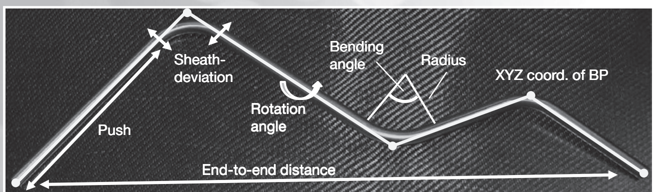
Measurement of bent parts

AICON 3d.systems



Measurement features

- Bending data PRB / LRA
- Tangent points / bending coordinates
- Sheath deviation
- End-to end distance, tube length



MEASURE THE ADVANTAGE

Measurement of bent parts

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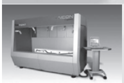
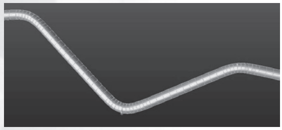
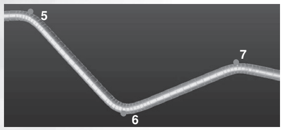


Tube with bending points (I)

- Measurement of a cylindrical model
  - Principles of photogrammetry
  - Complete 3D acquisition
- Detection of bending points
  - Search and assignment
  - Prediction of not detected bending points, e.g. in case of flat bends





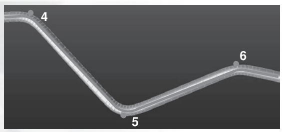
MEASURE THE ADVANTAGE

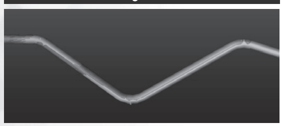
Measurement of bent parts

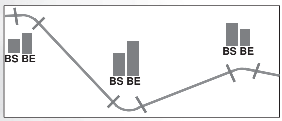
AICON 3d.systems

Tube with bending points (II)

- Calculation of bending elements
  - Based on measured cylinder model
  - Adjustment of bending model (PRB)
- Nominal-actual comparison
  - Graphical view of nominal and actual
  - Different views including sheath deviation
- Deviation and correction values
  - Sheath deviation for BS/BE
  - Based on bending model







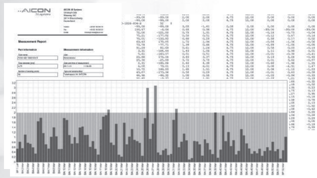
MEASURE THE ADVANTAGE

Measurement of bent parts

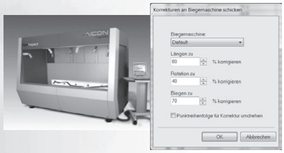
AICON 3d.systems

Tube with bending points (III)

- Reports and output
  - Display of different views
  - Reports containing measured data



- Correction of bending machines
  - Data transfer to bender
  - Selected data only
  - Damping of values possible



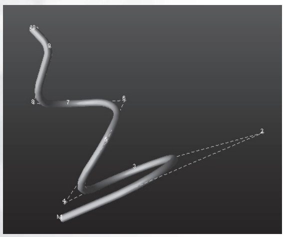
MEASURE THE ADVANTAGE

Measurement of bent parts

AICON 3d.systems

Freeform with bend data

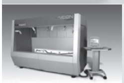
- Freeform BD
  - Bending data is available
  - Correction of bender is possible



MEASURE THE ADVANTAGE

Measurement of bent parts

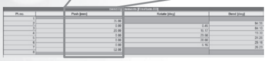
AICON 3d.systems



Freeform with bend data

- Characteristics of Freeform BD tubes
  - Variable bending radii
  - Push values are zero
- New evaluation method with TubeInspect

Push [mm]
35.00
→ 0.00
20.00
→ 0.00
→ 0.00
→ 0.00
52.00



Coordinates [Freeform-BD]

Pt-no.		X [mm]	Y [mm]	Z [mm]	Tolerance		Radius
FP	1	1403.32	627.53	2.19	1.00	1.00	0.00
FP	2	1344.03	607.62	28.26	1.00	1.00	30.36
FP	3	1373.50	552.84	40.94	1.00	1.00	34.06
FP	4	1429.73	570.10	17.41	1.00	1.00	74.22
FP	5	1457.89	591.88	4.13	1.00	1.00	118.09
FP	6	1485.64	634.37	-0.19	1.00	1.00	98.25
FP	7	1503.73	677.92	19.23	1.00	1.00	109.21
FP	8	1514.90	729.26	76.13	1.00	1.00	0.00

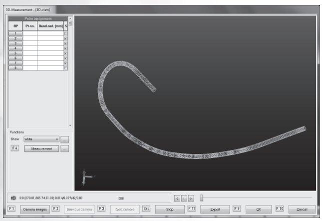
MEASURE THE ADVANTAGE

Measurement of bent parts

AICON 3d.systems

Measurement of a freeform geometry

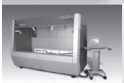
- 3D cylinder model is measured
- Special processing algorithm to calculate corrections
  - Segments are detected automatically
  - Bending data of measured geometry is derived
  - Correction values for the bending machine are calculated



MEASURE THE ADVANTAGE

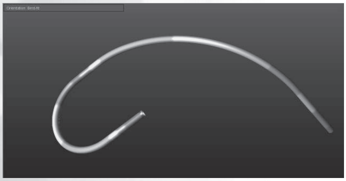
Measurement of bent parts

AICON 3d.systems



Evaluation of a Freeform BD tube

- Results:
  - Nominal-Actual view
  - Sheath tolerance (contour)
  - Bending data



Deviations of bending points

Report of tube measurement									
Complete name		Freeform-BD				Diameter		5.25	
Comments									
Date	2011/04/18	Time	17:50:44						
Additional information									
	Tube length [mm]		End to end dist. [mm]		Trim length [mm]				
	Actual	Error	Actual	Error	Begin	End			
	381.97	-0.03	168.13	-0.00	0.00	4.32			
Bending elements									
Pt.no.	Push [mm]		Rotate [deg]		Bend [deg]		Radius		
	Actual	Error	Actual	Error	Actual	Error	Actual	Error	
1									
2	33.57	-1.43			88.7	-5.7	32.31	1.95	
3	0.00	-0.00	2.6	2.2	83.7	-0.4	34.22	0.16	
4	15.26	-4.74	10.9	-4.3	15.7	-3.6	91.10	16.88	
5	0.00	-0.00	32.2	2.6	25.3	1.1	113.01	-5.08	
6	0.00	-0.00	26.6	-1.4	24.9	-4.3	115.05	16.80	
7	0.00	0.00	10.0	3.8	26.7	0.4	107.45	-1.76	
8	56.51	4.51							

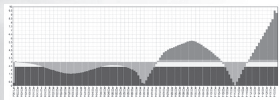
MEASURE THE ADVANTAGE

Measurement of bent parts

AICON 3d.systems

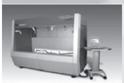
Freeform (contour inspection)

- 3D cylinder model is measured
- Contour inspection between nominal and actual data
- Any cylindrical geometry is compared
- Visual evaluation only
- Orientation is possible



MEASURE THE ADVANTAGE

Measurement of bent parts



Range of applications

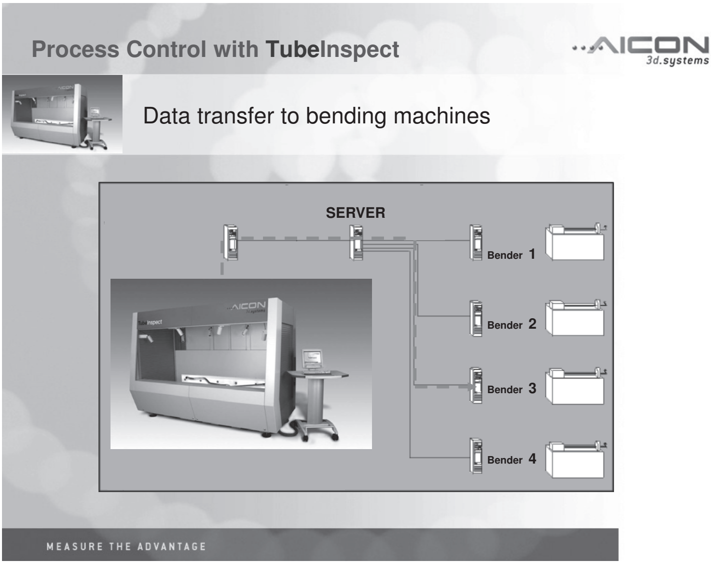
- Possibilities to evaluate a 3D measurement

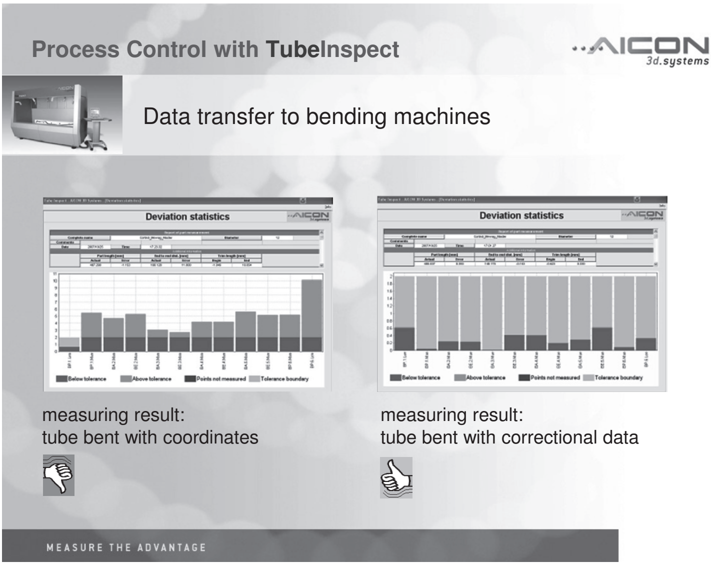
Tube with bending points	Freeform with bend data	Contour inspection
• Graphical nominal-actual comparison • Calculation of bending points • Display of bending elements and bending coordinates • Sheath tolerance test at start and end of each bend • Corrections for bending elements PRB • Issue of detailed protocols	• Graphical nominal-actual comparison • Calculation of freeform bending points • Display of bending elements • Sheath tolerance test • Corrections for the freeform geometry • Issue of detailed protocols	• Graphical nominal-actual comparison • Sheath tolerance test along the measured centerline • Issue of diverse protocols

MEASURE THE ADVANTAGE

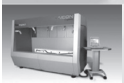
Process Control with TubeInspect

MEASURE THE ADVANTAGE


Process Control with TubeInspect
AICON
3d.systems
Data transfer to bending machines
SERVER
Bender 1
Bender 2
Bender 3
Bender 4
MEASURE THE ADVANTAGE


Process Control with TubeInspect
AICON
3d.systems
Data transfer to bending machines
Deviation statistics
Deviation statistics
measuring result:
tube bent with coordinates
measuring result:
tube bent with correctional data
MEASURE THE ADVANTAGE

Summary



Measurement of bent parts for the correction of benders

- AICON provides optical camera based 3D measurement systems
- TubeInspect allows the measurement of different tube types
- Measurement and evaluation of tubes with classical bending points and freeform geometries
  - Wide tube range
  - Software provides additional functionalities
- Automatic process control is possible
  - Correction of benders
  - Automatic mode for remote control

MEASURE THE ADVANTAGE

Variation of Contractile Strain Ratio of TA18 Titanium Alloy Tubes with Plastic Deformation

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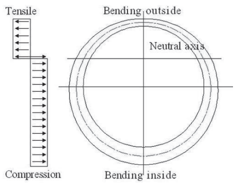
zhanmei@nwpu.edu.cn (M.Zhan)

Abstract: TA18 Titanium alloy tubes are materials with an obvious anisotropy. This paper studied the variation laws of contractile strain ratio (CSR, an index for anisotropy) of a TA18 high-strength titanium alloy tube by two computation methods. It is found that variation laws and range of CSR at different locations are different. And the CSRs obtained by two methods vary with strain similarly, but the CSR obtained by Method 2 is larger a little than that by Method 1 due to the thickness effect included in Method 2.
Keywords: anisotropy, CSR, tube bending, FEM, uniaxial tension

1. INTRODUCTION

As one kind of key lightweight components, titanium alloy tubes have been increasingly used and have a promising future for finding a wider application in the aerospace, aviation and related high-technology industries, due to their advantages of high-pressure resistance, a high strength/weight ratio and long life, and so on. However, titanium alloy tubes are materials with an obvious anisotropy. The anisotropy of tubes is usually described by contractile strain ratio (CSR). A tube with CSR>1 means that the deformation in width direction is easier than that in thickness direction. That is to say, it is not easy for the material to thin or thicken.

The CSR relates to the preferred orientation of crystal, evolution of texture, strain paths, plastic deformation degree, etc [Gilmour et al., 2004]. Xiangdong Wu et al., (2004) found that the CSR affected the plastic deformation behavior of anisotropic sheet metal. And it also affected the springback of tubes after bending [JIANG Zhiqiang et al., 2010]. Bending, bulging, flattening, and flaring are main plastic forming processes for the application of titanium alloy tubes. During these plastic forming processes, titanium alloy tubes will be deformed into various components under different stress states and deformation degree. For example, in the NC bending process of titanium tubes, defects of rupture of outer wall is due to over-thinning of outer wall under the action triaxial tensile stress, and defects of wrinkling of inside wall is due to over-thickening of inside wall under the action of triaxial compress stress (shown in Fig.1). The occurrence of these defects has the relation to the variation of CSR during the plastic forming process. But the CSR is always regarded as a constant independent of plastic deformation process in recent researches on the plastic forming of titanium alloy tubes, which may result in analysis error at some degree. Therefore, it is essential to study variation laws of CSR of titanium alloy tubes with plastic deformation to develop the plastic forming of titanium alloy tubes and extend applications of titanium alloy tubes. This paper studied the variation of CSR of a TA18 high-strength titanium alloy tube by experiment and FEM, and also analyzes measurement results.



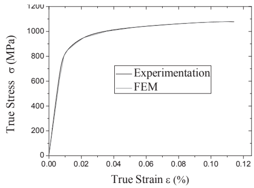


Figure 1. Characteristic of tube bending Figure 2. Stress-strain curves of TA18 tubes

2. MATERIALS AND METHODS

2.1. Material

The tubes used are TA18 high-strength titanium alloy ones made by Western Titanium Company. The tubes are 12 mm in outside diameter and 0.9 mm in thickness. The true stress-strain curves of the tube were obtained by tensile testing, as shown in Fig. 2.

2.2. Methods

Tube specimen with a plug for each end were used to measure the CSR, as shown in Fig.3. Uniaxial tensile testing of tube specimen was carried out by a CMT5205 electronic universal testing machine. The tension velocity is 3mm/min. In experiment a longitudinal extensometer and a transverse extensometer were used to record the variation of gauge length and diameter of TA18 tube specimens during uniaxial tensile deformation. The transverse extensometer was fixed on the middle of tube specimens.

To accurately reflect the variation laws of CSR of titanium tube in the plastic deformation process, two methods are used in this study. Method 1: In accordance with aerospace standard of contractile strain ratio testing of titanium hydraulic tubing, the CSR can be determined as CSR=-Ec/(Ea+Ec) , in which, Ec, Ea and Er are true circumferential strain, true axial strain and true radial strain, respectively. Method 2: According to the definition of the CSR, the CSR can be determined as

CSR=ln[(D1+d1)/(D0+d0)]/ln(t1/t0), in which, Do, do, to and D1, d1, t1 are outside diameter, inside diameter and wall thickness of tube before and after tensile, respectively.

An FE model for uniaxial tensile of a TA18 tube specimen was established using software Abaqus, as shown in Fig. 4. The gauge length of tube specimen is 50mm. By simulating the deformation process of TA18 tube specimens in the uniaxial tension, the variation of gauge length and diameter at different locations with time can be obtained.

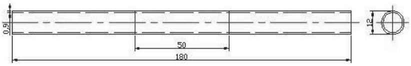


Figure 3. Tube specimen and plug

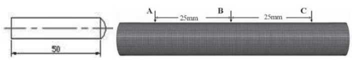


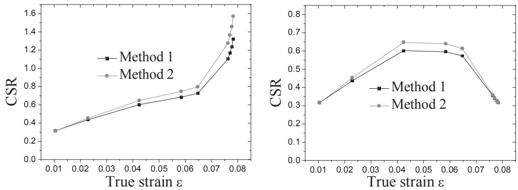
Figure 4. An FE model for uniaxial tensile of a TA18 tube specimen

3. RESULTS AND DISCUSSIONS

Fig. 5 shows variations of the CSR of end point of gauge length (Point A in Fig. 4) and the midst point of gauge length (Point B in Fig. 4) during the FEM simulation for tensile deformation of a tube specimen. From Fig. 5, it can be seen that the variation laws and range of CSR of points at different locations are different. As shown in Fig. 5(a), the CSR of the midst point (Point B) increases from about 0.3 to 1.6 with the increase of strain during the tensile plastic deformation, however the increase slope varies a lot during the process. In the beginning the increase is slow, in the midst stage the increase is rapid, and at final stage the increase becomes sharp. As shown in Fig.5(b), the CSR at the end point (Point A) increases at first, then varies a little and decreases finally, and CSR changes in a range of about 0.3 to 0.65. The different variation laws of CSR at different locations may be result from different plastic deformation degrees. The more close to the midst of the tube specimen the location is, the more thorough plastic deformation occurs. This leads to an obvious change of CSR in the midst.

Fig. 6 shows variations of the CSR of the midst point of gauge length during the experiment for tensile deformation of a tube specimen. As seen from Fig. 6, an increase occurs in the beginning and a slight decrease in the later deformation stage. This variation trend is similar to that of the midst point by FEM. But the variation ranges of them are different. The CSR of the midst point by FEM changes in the range of 0.3-1.6 and the CSR by experiment changes in the range of 0.09-0.61. This difference may result from the slip and displacement change between the sample and the extensometer.

As seen from Fig. 5 and Fig. 6, the CSR values obtained by two methods almost equal to each other in the former plastic deformation stage. But in the latter plastic deformation stage, the CSR obtained by Method 2 becomes larger than that by Method 1. And the difference becomes obvious as plastic deformation increasing. This may be due to the thickness effect are included in Method 2.



(a) Point B *(b) Point A*

Figure 5. CSR -strain curves of TA18 tubes from FEM

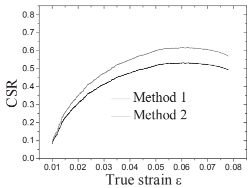


Figure 6. CSR -strain curve of TA18 tubes from experiment

4. CONCLUSIONS

(1)The variation laws and range of CSR at different locations are different. The CSR in the midst increases faster and faster with the increase of strain during the tensile plastic deformation. The CSR at the end increases at first, then varies a little and decreases finally, and the CSR changes in a range is less a lot than that in the midst. (2)The CSRs obtained by two methods vary with strain similarly, but the CSR obtained by Method 2 is larger a little than that by Method 1 due to the thickness effect included in Method 2.

ACKNOWLEDGEMENTS

The authors would like to thank the National Natural Science Foundation of China (51175429), the Fund of New Century Excellent Talents in University (NCET-08-0462) , the Fundation of NWPU (JC201136), the Fund of the State Key Laboratory of Solidification Processing in NWPU (KP200919) and the Project of 111(B08040).

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[JIANG Zhiqiang et al., 2010] JIANG Zhiqiang. Deformation laws of mediumstrength titanium alloy thick-walled tubes in NC bending process [D]. Northwestern Polytechnical University, 2010.

Session 6: Tube Bending

Improving the Curvature of Bent Profiles by Adjusting the Process Kinematics of the Three-Roll-Pushbending Process

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Abstract: Three-Roll-Pushbending is a conventional Freeform-Bending process to manufacture bent profiles with variable radii and radii distributions along their longitudinal axis. The shaping is done kinematically by varying the position of the forming-tool and the axial feed of the profile. Measurements of the resulting curvature of the bent tube have shown a characteristic periodical distribution over an extensive length of the part until a constant radius is reached. Such inadvertent transition zones have to be avoided. This paper presents a strategy for the Three-Roll-Pushbending to smooth and shorten the transition zones by adjusting the process kinematics.
Keywords: Freeform-Bending, Three-Roll-Pushbending, process kinematics

1. INTRODUCTION

The task of forming technology is to manufacture parts of low weight providing a maximum of functionality at the same time. Therefore formed profiles are increasingly used these days [Gantner et al., 2007]. They feature a beneficial ratio of rigidity to weight and therefore are commonly applied for lightweight construction. The manufacturing processes require a high flexibility. They have to be both suitable for series production as well as cost-efficient. Freeform-Bending processes meet these standards by bending straight-lined profiles with variable radii and radii distributions along their longitudinal axis.

2. PROCESS KINEMATICS OF THE THREE-ROLL-PUSHBENDING

The shaping of the Freeform-Bending-Processes is done kinematically. Although there exist different methods of Freeform-Bending, the principle of the forming procedure is basically the same. The profile is guided axially through stationary supporting tools, either a cavity or rolls. The forming force is transmitted to the profile by positioning a movable die (a cavity, a roll or a combination of rolls) relatively to the stationary tools, while the profile is simultaneously fed forward in longitudinal direction by the means of a pusher. At the University of Siegen research is done on the Three-Roll-Pushbending (TRPB) process. TRPB is a Freeform-Bending process, which is - in accordance with Plettke et al., 2010 - mainly used for bending geometries consisting of several plain bending curves on different bending planes. A schematic illustration is shown in figure 1.

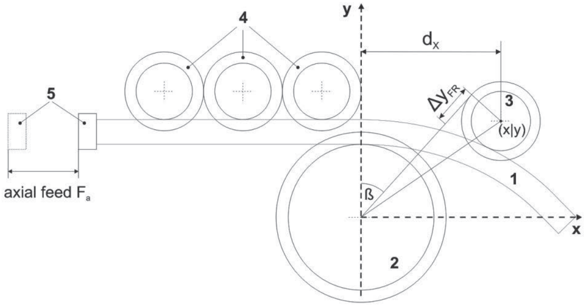

Figure 1: Schematic illustration of the TRPB process.

The bending-roll (2), the supporting-rolls (4) and the pusher- and rotation-unit (5) guide the profile (1) in longitudinal direction. The forming-roll (3) effects the bending moment by being positioned towards the profile. Using the pusher- and rotation-unit (5) the profile is fed forward. The TRPB can be applied on a conventional rotary-draw-bending machine. The forming-roll is mounted on the bending-arm, whereas the supporting-rolls and the bending-roll replace the pressure die and the bend die, respectively.

The process kinematics, the coordinated movements of the forming-roll and the profile during the bending process, define the curvature distribution of the bent profile. In simplified terms, two kinematic conditions can be distinguished. Is the position of the forming-roll changing while the profile is fed forward concurrently, a radii distribution is obtained. A constant radius is being bent if the forming-roll stays stationary during the axial feed of the profile. In addition to the positioning of the forming-roll, the deflection of the machine, the springback of the profile and the positioning accuracy especially of the forming-roll influence the bending result. The shorter the horizontal distance between the centre points of the forming-roll and the bending roll in x-direction dx, the bigger is the deviation of the resulting radii while slightly changing the y-position. Therewith, the inaccuracy in positioning the forming-roll has an increasing negative impact on the bending result when the distance dx is decreasing. Furthermore, the shorter dx, the bigger is the needed forming force to effect the same bending moment. Therefore a bigger distance dx is preferred.

Although constant radii should be bent, measurements by Engel and Kersten, 2010 of the resulting curvature of the bent tube (Fig. 2) have shown a characteristic periodical distribution over an extensive length of the part until a constant radius is reached. This transition zones occur with every initial bending step when the straight profile is loaded with the transmitted force for the first time.

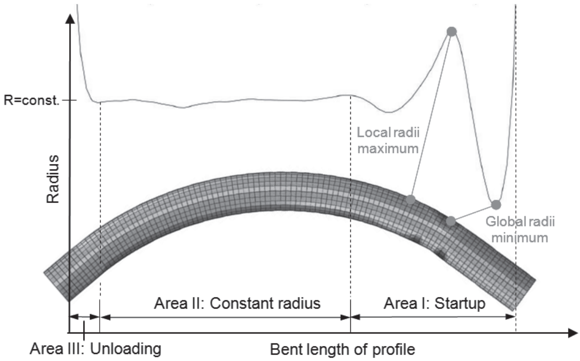

Figure 2: Radii distribution along the longitudinal axis of a bent profile.

From this point of view, a shorter distance dx resulting in shorter transition zones is favoured. However, the forming-roll does not necessarily have to be fixed in one position to bend a constant radius. Regarding the TRPB process, the forming-roll may as well move with an appropriate speed to the axial feed of the profile on a circular path, which is concentric to the bending radius (Fig. 3).

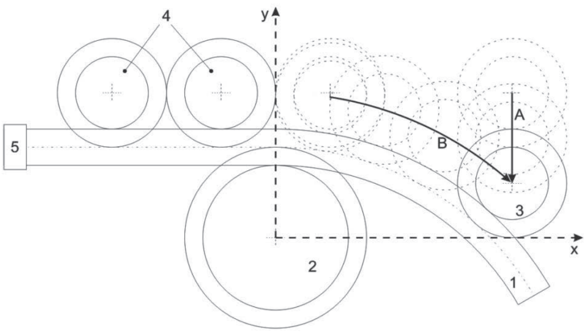

Figure 3: Comparison of startup-strategies A and B.

The movement of the forming-roll can be achieved by moving the bending-arm by the value of β while advancing the forming-roll in direction of the bending-arm by the value of ΔyFR (Fig.1). The on-line startup-strategy (Strategy B) is shown in comparison to the conventional linear startup-strategy A. Several tests on both strategies were run at the Chair of Forming Technology in Siegen (UTS) using defined tube specimen (diameter: 20 mm, wall thickness: 1 mm). The resulting radii distributions along the length of the tubes are illustrated in figure 4 by one example of each startup-strategy.

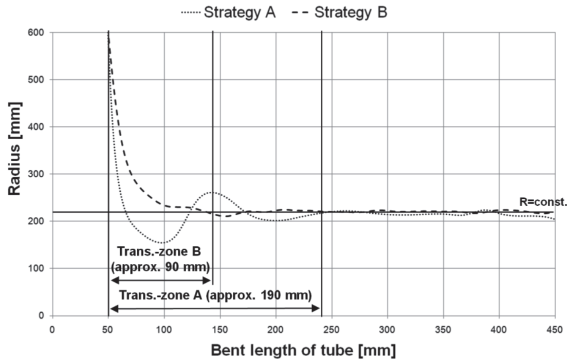

Figure 4: Resulting radii distributions for startup-strategies A and B.

3. CONCLUSIONS

It can be stated, that the transition zone is shortened by more than one half using the on-line startup-strategy B instead of the conventional linear startup-strategy A. In the same way the oscillation amplitudes of the transition zone are reduced as well. Thus, the contour accuracy of the bent profile can be improved by adjusting the process kinematics without much ado.

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Influence Factors of Three-Roll-Push-Bending

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Abstract: Three-roll-push-bending is a flexible, kinematic bending process for tubes. The bending tools can be positioned to achieve the bending geometry by pushing through and rotating the tube. This process has many influencing factors which can be divided into control and disturbance factors. The paper will present the known factors. A simulation based study of the influence of friction between bending tool and tube in three-dimensional free form bending will be discussed in detail. In order to investigate this influence a new simulation model based on the finite element method was built up and validated against experimental values.
Keywords: Three-roll-push-bending, finite element method, influencing factors

1. INTRODUCTION

Bent metal tubes find widespread application in many sectors of industry. A new free form bending processes is three-roll-push-bending and has been researched by Gerlach [Gerlach, 2010] and Merklein [Merklein et al., 2009]. While this process is flexible and able to produce non-constant 2D- and 3D-curvatures, it was shown that numerous influencing factors lead to poor predictability of the process. A possible solution to compensate this is the integration of optical measurement devices [Kim et al., 2009] and automatic correction. This trial-and-error approach leads to a certain amount of waste material and production downtime. To avoid this a numerical model of the three-roll-push bending process has been developed. The working principle of the three-roll-push-bending process, which bases on two holding rolls, one bending roll and one setting roll, is based on P-, Y-, C- and A-axis, as shown in Figure 1.

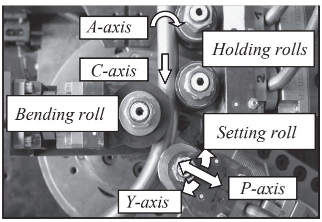

Figure 1; Tools and axis of the three-roll-push-bending machine.

An arc as a bending geometry is defined depending on the position of the setting roll given by P- and Y-axis and the feeding rate of the C-axis. Investigations have shown that the bending radius as target value by bending an arc is affected by many influences. For better comprehension of these factors Taguchi´s method has been applied. These factors were classified after G. Taguchi [Kleppman, 2006] in two groups of control and disturbance factors. The identification of the most significant influencing factors was done after extensive experimental work had been finished and discussed by Plettke [Plettke et al., 2010]. These factors have been published and discussed by Hagenah [Hagenah et al., 2010]. The primary aim of Taguchi´s method is to minimize variations in the target value caused by disturbance factors which are present in the process. The process is then said to have become robust. This can be applied to three-roll-push-bending processes by evaluating the effect of each single disturbance factor on the target value. For this sake the numerical investigation of the process has been done.

Numerical investigation of the process has begun using simple finite element models, where only the kinematic of the P-, Y- and C-axis has been modeled. This model suffered from a deviation up to 20% between simulated and experimentally defined bending radius R [Cojutti et al., 2009]. To improve simulation results the machine deflection as disturbance factor has been simulated in the second numerical model [Hagenah et al., 2010]. Respecting the machine deflection, the predictability of the process was improved by 10% and this gives an overall precision of about 90% in prediction of the FE-model. The remaining 10% are caused by further disturbance factors and therefore lead to variations in the target value.

All investigations up to now were focused on the bending geometry arc, with the bending radius R being the target value, which can be bent by setting the P-, Y- and C-axis. Beside these axes the tube can also be rotated during the bending process by the A-axis, (see Figure 1). To investigate the influence of the tube´s rotation by the A-axis, the FE-model was enhanced and validated against experiments.

2. SIMULATION OF THE THREE-DIMENSIONAL FREE FORM BENDING

The three-roll-push-bending process allows us to bend different kinds of bending geometries. These geometries cannot necessarily be described by a set of bending radii in all cases. Especially when employing the A-axis, the need for the redefinition of the general target value, other than the bending radius R, has appeared. Investigating three-dimensional bent tubes needs the definition of the bending result not only in terms radius, arc length and angle, but also in terms of torque. To understand what happens during the bending process two simplified models have been set up. These models distinguish two-dimensional free form bending (2DFB) from three-dimensional free form bending (3DFB). The 2DFB model allows only the observation of the bending moments Mb produced by the position of the setting roll, while in 3DFB an additional deformation mode, i.e. the torque Mt of the tube around its axis of symmetry, produced by the A-axis, can be defined, Figure 2.

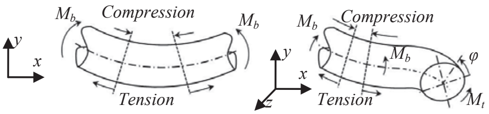

Figure 2; Left hand side picture shows 2DFB and right hand side 3DFB.

As result of the torque a helix will be bent [Soler et al., 2006]. This bending geometry can be now used to investigate the influencing factors during 3DFB. The target value will be the comparison of the position of the end part of the helix in reality and model. The difference shall be minimized.

The experiments were conducted on a three-roll-push-bending machine Wafios BMZ 61. The working principle has been explained in detail in [Hagenah et al., 2010]. The tube used in this experiment was made of carbon steel St 37 with an outer diameter of 20mm and a wall thickness of 1mm. A helix was chosen as target bending geometry. Since this was a preliminary investigation a helix with a randomly defined radius of 100mm and torsion of 80° for the feeding length of 400mm was chosen. To bend the selected geometry, the process parameters for P- and Y-axis were defined based on characteristic lines and set to P=31.5° and Y=37.43°. In order to achieve the torsion, the rotation of the A-axis was programmed accordingly.

For the numerical investigation of 3DFB the improved FE-model presented by [Hagenah et al., 2010] was used as a basis. This FE-model uses the program Abaqus 6.8 and is solved by the Abaqus explicate solver. Since it was meant to simulate the 2DFB, some adaptions had to be carried out. The original 2DFB FE-model was remodeled to include also the lower half of the geometry, the symmetrical plane was removed. Since 3DFB demands rotation of the tube, the kinematic of the tube has been updated to simulate the A-axis. All other parameters of the FE-model remained the same as already described in [Hagenah et al., 2010].

To compare the simulation results with the experiment, the bent helix was measured with the optical measurement system ATOS I [Bergmann et al., 1997]. The result was an STL-model. This model was compared to the computational model. The two models were registered in one coordinate system. The parts of the tube that were clamped and not bent were fit to each other using a best fit algorithm [Schneider et al., 2008]. Doing this a difference of 29.7 mm between computation-Abaqus and measurement-STL can be seen, as shown in Figure 3 on the left hand side. In order to reduce the deflection the 3DFB FE-model was further improved by introducing anisotropic friction conditions. The rotation of the tube causes sliding-friction μg on the walls of rolls besides the roll-friction μr. To simulate this friction phenomenon the anisotropic friction model for deformable surfaces [Pabst et al., 2010] has been adopted. The roll friction was defined as μr = 0.05, which is comparable to the case of a steel roll rolling on a steel plate [Fischer et al., 2005]. For the sliding friction a value of μg = 0.25 was defined which is similar to the friction case when a steel plate slides on another steel plate [Fischer et al., 2005]. On the right hand side of figure 3 the improvement of the results in terms of maximal deflection which was reduced to 24.7mm on the end of the Helix.

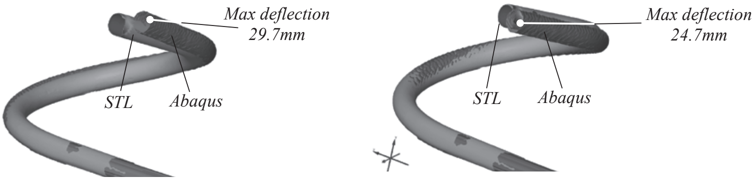

Figure 3; Comparison between experiment and computational model – left hand side with isotropic friction model, right hand side with anisotropic friction model.

3. SUMMARY AND OUTLOOK

Considering friction this numerical based investigation of 3DFB shows noticeable improvement in computational precision of the FE-model. Respectfully this phenomenon cannot be neglected. In future work this preliminary model will be improved by determining the precise friction coefficients experimentally.

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Imprint:

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Forming Technology and
Lightweight Construction

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