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The Process of Bending Pipes for Components of Aircraft Frames and Trusses

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ABSTRACT

Demand for bent pipe profiles in various industrial sectors is increasing due to considerations necessitating lightweight construction, safety, as well as space and cost savings. Lightweight construction is becoming increasingly important for economic and ecological reasons. This can be seen in the automotive and aerospace industries, as well as in civil engineering, where curved structures are often required. In order to reduce the weight of the aircraft, the aviation industry often uses spatial truss structures with bent elements. The challenge is to meet all of the stringent requirements regarding design, safety, structure, size, cost, etc., without compromising a structure's stiffness. Profiles with complicated cross-sections and so-called tailored tubes are increasingly used in the production of automotive and aircraft structures (General Aviation). Pipe and profile bending technologies are constantly being improved upon to meet the growing expectations of customers and ensure greater process efficiency. Currently, efforts are being made to increase the level of automation in this area by combining the functionality of modern bending machines with the capabilities of industrial robots. CNC bending machines currently dominate the industrial pipe bending process. A technologically advanced bending machine allows for the production of increasingly complex shapes and profiles.

Keywords: forming, bending, tube bending, steel tube bending, tube springback.

INTRODUCTION

In the pipe bending process, high-strength materials (such as 1.7734 steel) and special parts with variable wall thickness - which are increasingly common in pipe and profile products - pose a serious challenge. Cracks in elements at small bending angles often constitute indicate the use limit for the application of a given material. Fixed die geometry during free bending is not useful for bending complex shapes. Due to these problems, there is great demand for the creation of new innovative variants of the free pipe bending process. In order to assess the effects of this technological procedure, it is necessary to simulate the bending process. The input data for the simulation is the geometry of the cross-section and geometry of the bent object in 3D CAD format and material data determined by the flow and hardening curve, as well as important values such as Young's modulus (E = 195.8 GPa) and Poisson's ratio ν = 0.3 (data for steel 1.7734.5). The first step is to analyse the bending geometry using different bending radii R and, in the case of a 3D bending part, different bending planes along the main section of the cross-sectional axis *Cx*. The next step is to perform semi-analytical calculations for each Rx ray to calculate the springback phenomenon and the compensated *Rk*, a, and *C* values that should be taken to obtain the target contour after unloading. These calculations should take into account the stiffness of the machine and the bending line and bending moment of the profile caused by the roller tools of the machine. Using this data, the bending geometry is iteratively redesigned, generating the final 3D part. The compensated part is then used to generate NC code through kinematic simulation. In the case of the analysed pipe forming process, the empirical formulas were not accurate enough, so numerical calculations using the finite element method (FEM) were determined by utilizing a computer simulation of the bending process [1, 2, 3].

MATERIAL DATA OF BENT PIPES

Steel marked according to DIN 1.7734 is a structural steel, a chrome-molybdenum-vanadium alloy intended for load-bearing parts of aerospace machines. It is used to produce parts of rocket engines and electric motors, light and durable elements of aviation devices and structures, frames of racing vehicles, and responsible components in the nuclear and armaments industry. It is characterized by very good mechanical and plastic properties, elasticity, and weldability in the heat-treated state. This steel is an alternative to the 30HGSA grade in aerospace and defence applications. At the same time, it is easier to weld. It is delivered in the form of bars, seamless pipes, forgings or flat products. The chemical composition of steel 1.7734 is included in Table 1. Steel 1.7734.5 is available in semi-finished products in a heat-treated condition.

The tested pipes had the following geometric dimensions: external diameter D = 20 mm, thickness g = 1 mm, bending radius R = 91 mm and bending angle α = 162.5° Strength tests of samples with a tubular cross-section D=16, thickness g=2 mm, 250 mm long and 150 mm measuring length made of material 1.7734.5 were carried out based on the standard: PN-EN ISO 6892-1: 2020-05 - Metals - Tensile test - Part 1. On a section of 50 mm, a core made of a D=12 mm rod was inserted from each end. During the tests, the environmental conditions described in the PN-EN ISO 6892-1: 2020-05 standard were maintained, i.e.: temperature 23°C ± 2°C (73.4°F ± 3.6°F), relative humidity 50% ± 5%.

The steel hardening curve is a mandatory parameter for plastic processing of metals. The relationship between the yielding stress and the equivalent plastic strain in the process of plastic deformation of steel allows for a numerical analysis of the bending process.

This curve describes the changes in the mechanical properties of steel under cold deformation. The hardening curve is an important parameter to determine the force and work needed to perform plastic forming operations, such as rolling, drawing, forging, bending, etc. The hardening curve of steel depends on many factors, such as chemical composition, crystal structure, grain size and shape, type and number of network defects, temperature and strain rate. There are various methods for determining the steel strengthening curve, e.g., tensile test method, compression test method, or internal friction test method. In the tests in question, a curve was determined using a uniaxial tensile test (Fig. 1) and then extrapolated using the Krupkowsky-Gesetz method (Tab. 2).

The determined curve is shown in Figure 2. The strengthening curve can be determined using the Krupkowsky-Gesetz hypothesis formula:

$$\sigma_w = K(\varphi + \varphi_0)^n \quad (1)$$

where: σ_w – stress, φ, φ_0 – strain, φ_1 and φ_2 – transition points for curve extrapolation K [MPa]- constant

The strengthening curve was determined using the Krupkowsky-Gesetz method, i.e. stress and strain values from an actual tensile test in the amount of 5000 pairs of values (stress and strain), which were extrapolated using two transition points (marked in red on the graph) φ1 and φ2 (breaking the curve), as well as Krupkowski parameters (*K, n)* The development of the technology for spatial bending of tubular bars made of 1.7734.5 steel requires taking into account the mechanical and technological properties of this material. 1.7734.5 steel is an alloy steel with high strength and good weldability, mainly used in the aviation and automotive industries

Table 1. Chemical composition of steel 1.7734 [14]

Content of alloying elements [%]									
C	Mn	Si	P	S	Cr	Mo	V	Ni	Cu
0.12–0.18	0.8–1.1	<0.20	<0.020	<0.015	1.25–1.50	0.8–1.0	0.2–0.3	–	–

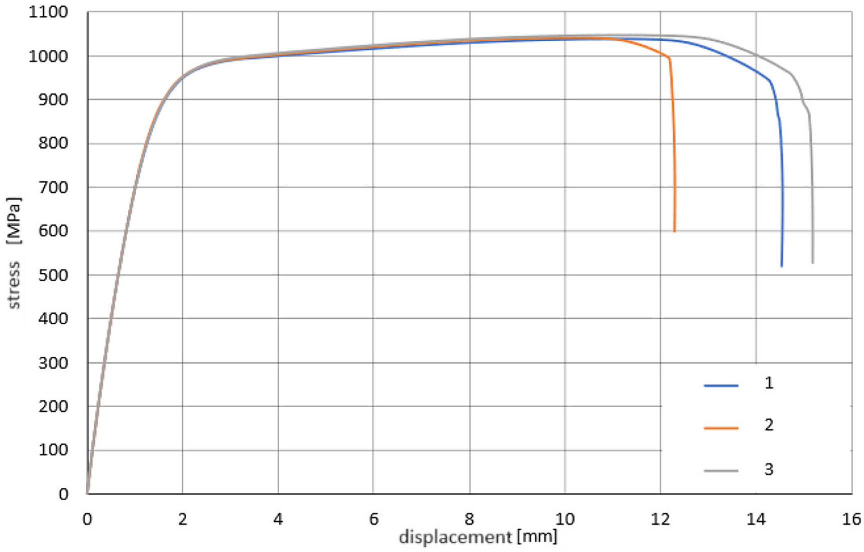

Figure 1. Uniaxial tension diagram of a sample made of steel 1.7734.5

with the composition given in Table 1. The mechanical properties of steel 1.7734.5 are: yield strength: min. Re = 1100 MPa, tensile strength: min. Rm = 1250 MPa, elongation: min. 8%, impact strength: min. 30 J [14]. To develop the technology of spatial bending of tubular bars made of steel 1.7734.5, an appropriate method and bending machine were selected: the CNCE-TURN52 bending machine. It was also necessary

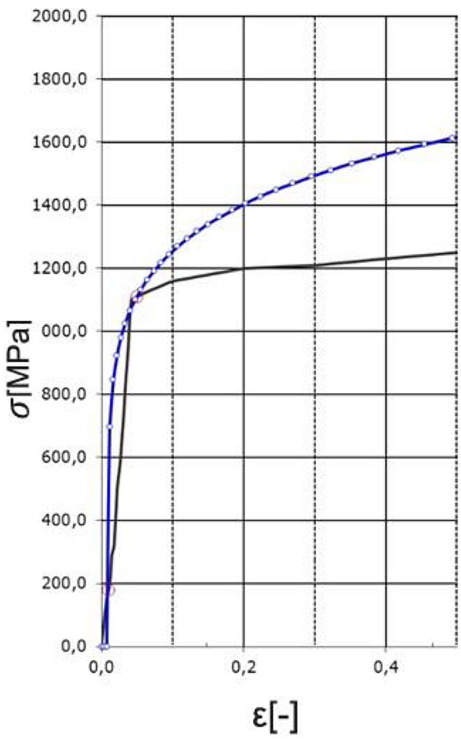

Figure 2. Strengthening curve determined using the Krupkowsky-Gesetz method for steel 1.7734.5

to determine the parameters of the bending process, such as bending force, bending radius, bending angle and bending temperature, which depend on the diameter and wall thickness of the pipe and on the requirements for the surface quality and shape accuracy of the bent element. In the bending process, the springback effect occurs when the material tries to return to its original shape after being bent. Springback depends on many factors, such as wall thickness, material strength, type of tools used, and bending method. To calculate the springback of a bent steel pipe, one needs to consider the bending angle, springback angle, and internal radius of the bend. The bend angle is the angle to which the operator bends the pipe to compensate for springback. The springback angle is the difference between the bending angle and the desired angle. The inside bend radius is the distance from the center of the pipe to the point where the pipe bends. The springback angle can be estimated from the empirical formula:

Table 2. Parameters of extrapolation of the strengthening curve of steel 1.7734.5 using the Krupowsky method

n	0.15000
φ_0	-0.001
K	1798.927
φ_1	0.001
φ_2	0.050

$$DEG = \frac{Ir}{Mt} U \quad (2)$$

where: DEG – springback angle in degrees, *Ir* – internal bending radius [mm], *Mt* – material thickness [mm], *U* – material coefficient, which depends on the type of steel [4, 5].

This formula is approximate and applies to bending in the bottom or free state configuration. For other bending methods, such as wipe bending or rotary bending, the springback angle may be different and more difficult to calculate. In such cases, it is best to perform a bending test and measure the springback angle experimentally. The material U factor describes the relationship:

$$U = 14 + 0.25 \cdot R_m \quad (3)$$

The bending force is marked with the symbol F. This force depends on many factors, such as material properties, cross-sectional shape, angle and bending radius.

$$F = \frac{2\pi t^2 E R_\alpha}{360D} \quad (4)$$

where: *F* – bending force, *t* – pipe wall thickness [mm], *E* – Young's modulus of the material, *D* – external diameter of the pipe [mm], *R*α – bending angle in degrees.

Cold bending of pipes manifests itself in several phases, i.e., initially there is a change in shape (elastic phase), and then, to some extent, this is replaced by a plastic change in shape. If the material's transforming ability is exhausted, the workpiece will crack. The elastic-plastic properties of metallic materials are reflected in the stress-strain diagram and determined in tensile tests. In the elastic range (Hooke's law), the tensile specimen undergoes elastic deformation. When the stress is released, the pipe returns to its original shape. However, if the stress exceeds the elastic limit, the shape of the sample is permanently changed. Shape changes occurring during bending of metal pipes are mainly determined by material-specific parameters: elastic and plastic moduli. Due to the elastic-plastic behaviour of metal materials, the pipes spring back and retract at a certain angle after each bending attempt. In addition to elasticity, there are other phenomena that must be taken into account when shaping pipes. In particular, this applies to the springing of the radius accompanying bending, oval deformations of the cross-section (round pipes) and changes in the length of the workpiece and the formation of folds. In order to verify the bending of the pipe in question, numerical simulations were performed to refine the best forming method to achieve the given geometry [6, 7].

FEM NUMERICAL SIMULATIONS OF THE BENDING PROCESS

The results of the simulation process are shown in Figures 3–7. In Figures 3 and 4, the FEM results prove that the material thinning is below 20%, therefore it is consistent with the standards adopted for steel materials. In Figures 5 and 6, the reduced stresses according to the HMH Hypothesis indicate the maximum reduced stresses near the material strength limit, but if thinning is permissible, this is within the norm. A test of pipe ovalization was carried out through experimental tests in the transit-intransitive test, as well as numerical and experimental tests of wall wrinkling. Wrinkling was allowed at a level of 5% and was finally found to be within the norm. The forming limit diagram (FLD) curve (Fig. 7) is a tool used to assess the formability of materials. This is a graph showing the relationship between principal strains and secondary sheet metal subjected to the stamping process. The FLD curve defines the limit above which cracks or folds in the material occur. The FLD curve depends on the type of material, its mechanical properties, thickness, temperature and strain rate.

This curve is often used to verify the accuracy of the stamping process and bending sheet metal before making forming tools. Thanks to computer simulation, you can check whether the part meets the formability criteria, i.e., whether it has cracks, folds, cosmetic defects, or springback. If the simulation shows problems with the formability of the part, changes to the geometry of the part in the stamping process or a change in material can be proposed. One step solver is a numerical method that allows for quick verification of the initial stamping or bending concept for producing parts and parameters such as thinning, stresses, and FLD areas.

In addition to one step solver simulations, other simulations were performed based on the incremental solver, which is more accurate and advanced than the one step solver. The incremental solver is a FEM numerical method that allows for precise mapping of the plastic forming process step by step, taking into account changes in geometry, material, and contact between the part

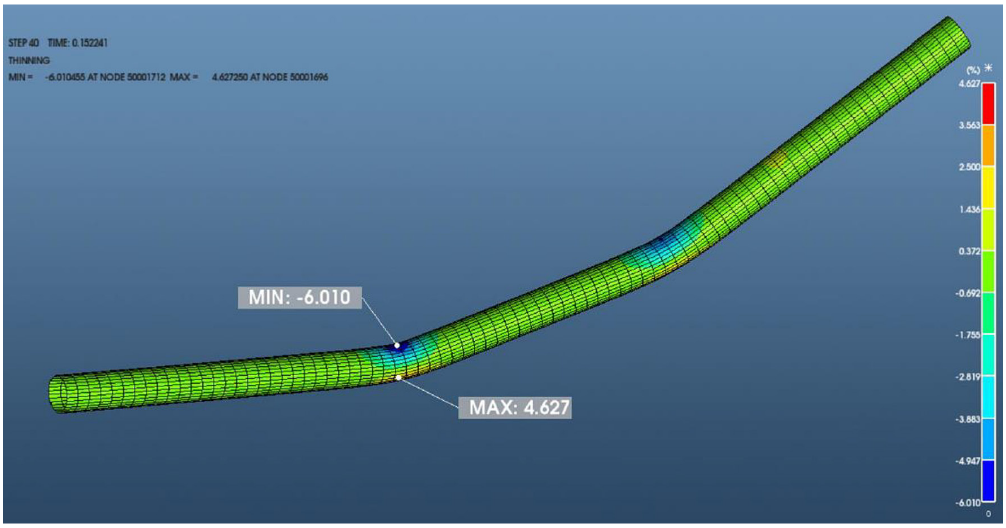

Figure 3. Pipe wall thickness on the inside expressed in mm, as determined by incremental solver simulation

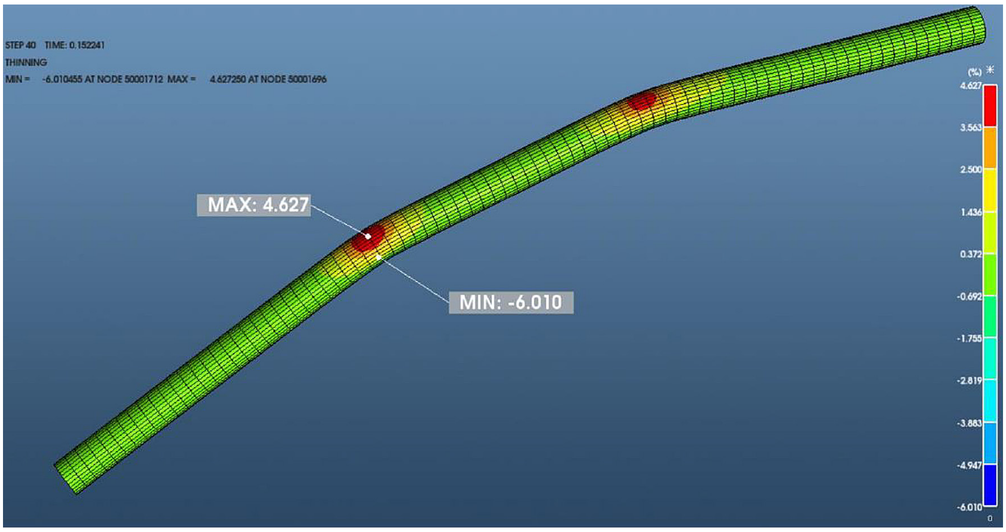

Figure 4. Pipe wall thickness expressed in mm from the outside, as determined by incremental solver simulation

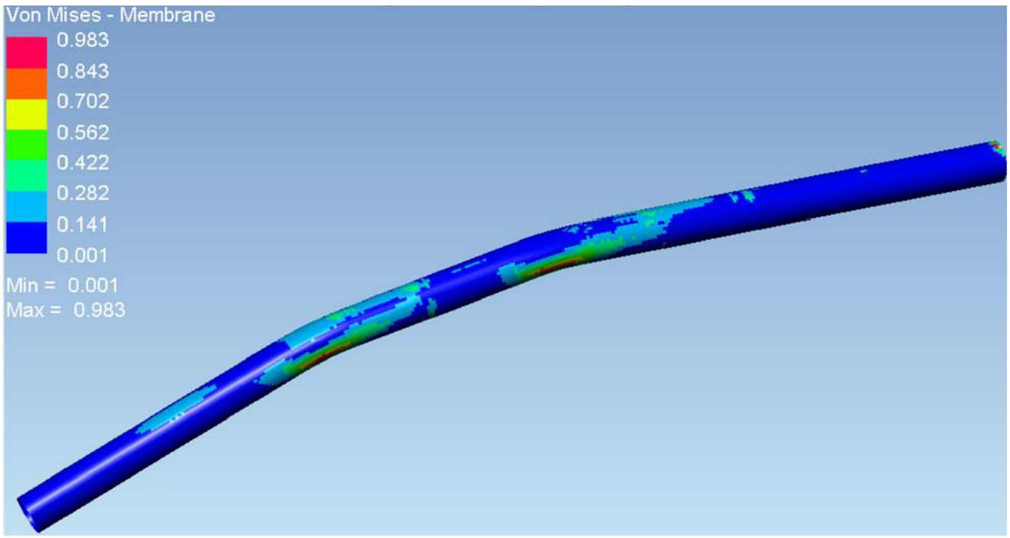

Figure 5. Stresses calculated according to the HMH hypothesis as determined by incremental solver simulation [GPa]

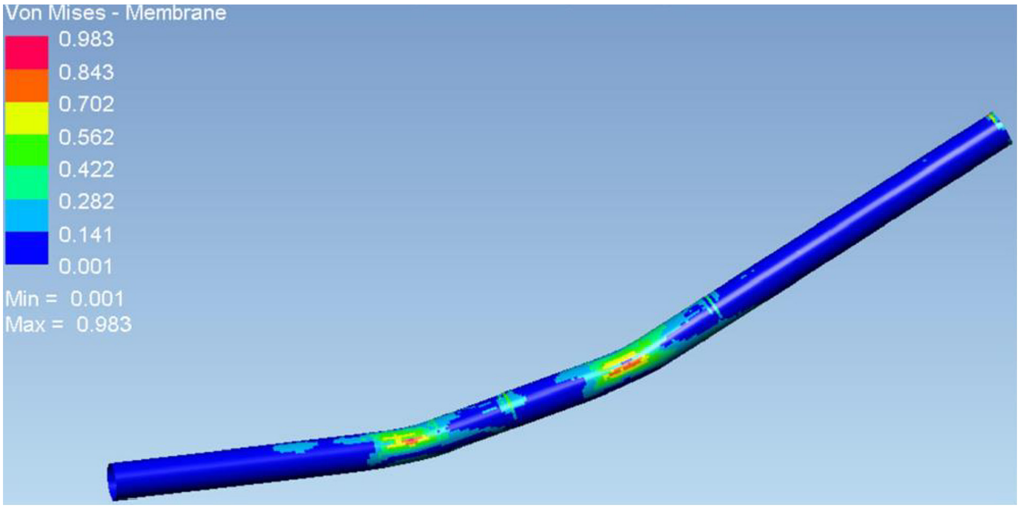

Figure 6. Stresses calculated according to the HMH Hypothesis as determined by incremental solver simulation [GPa]

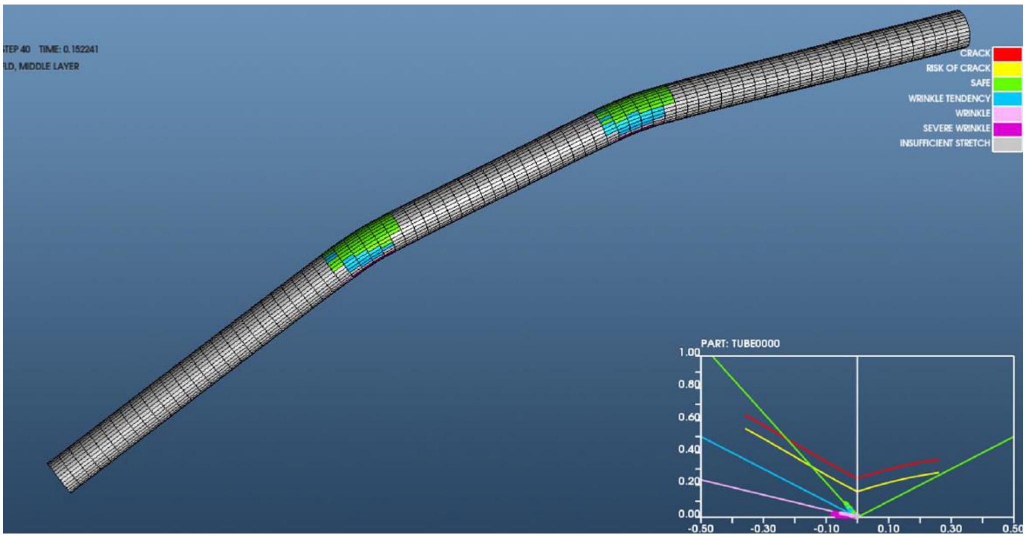

Figure 7. FLD curve as determined by incremental solver simulation

and the tool (Fig. 8). The incremental solver also enables optimization of the machining process, e.g., by adjusting the position and shape of holes or cutting lines [8].

SPRING EFFECT

The concept of elasticity of elements formed by plastic processing is a consequence of the spring effect of the pipe after bending, when the process is completed and the pipe leaves the die or mandrel, remaining free. Being within the scope of Hooke's law, the energy during shaping is completely transferred as elastic deformation work in the form of elastic energy. In this case, the extent of springback is caused only by the elastic (reversible) part of the forming work, i.e., it's stored in the pipe as potential energy during the bending process. Springback is an unavoidable phenomenon of bending and can only be compensated for by excessive bending of the workpiece. In order to determine the amount of springing of the structure, in a considered case, a simulation of this process was carried out. The simulation results are shown in Figure 9. The obtained test results indicate that in the case under consideration the maximum values of return springing are significant, reaching a value of approximately 4.82 mm at the end points of the pipe. This indicates the need to verify the bending process to maintain a shape that meets the tolerance conditions.

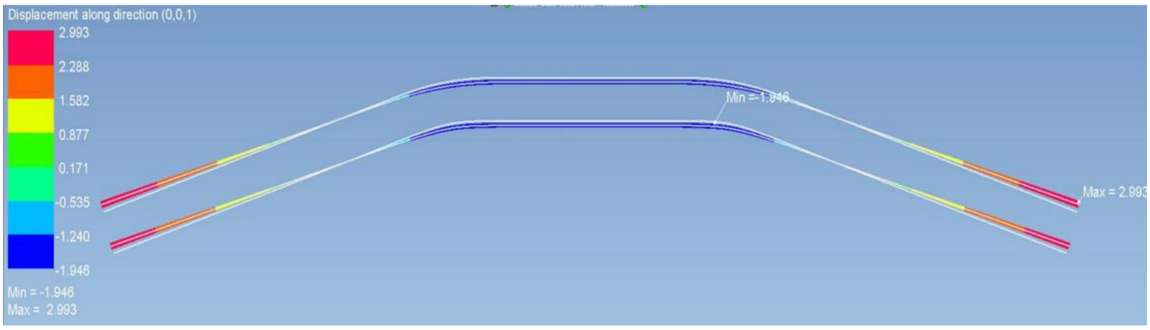

Figure 8. Springback as determined by incremental solver simulation

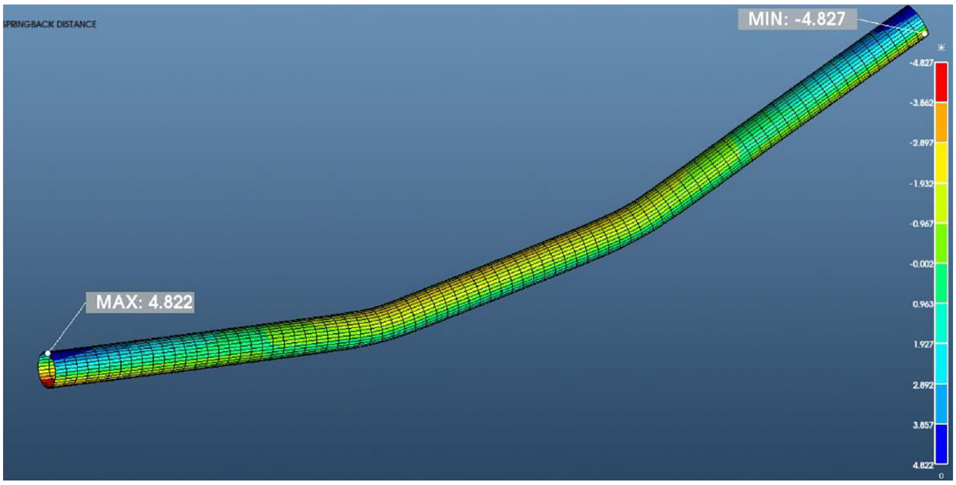

Figure 9. Springback as determined by one step solver simulation

When bending round pipes, the pipe walls are subject to longitudinal bending. The resulting stress state leads to an oval distortion of the round pipe cross-section. The outer side of the shaped surface limited by the bending radius is inclined to the center line, which causes the pipe to flatten, and its allowable size is limited by the shape tolerance. The balance of forces acting during the bending process shows that the pressure forces created due to the bending moment in the inner part of the pipe bend and the tensile forces in the outer bend area of the pipe act in opposite directions, thus promoting the compression of the original circular cross-section, which may lead to folding (Fig. 10) [9, 10].

EXPERIMENTAL RESEARCH

In order to quantitatively assess the occurring unfavourable phenomena, experimental tests of the bending process were carried out. The test result is shown in Figure 11. This effect can be reduced by using pre-tension. The larger the ratio of the pipe's outer diameter to its wall thickness and the smaller the bending radius, the greater the tendency of the pipe to form wrinkles when bending. The quality of a bent part can be assessed based on:

- metric measurements,
- in an attributive way (classification on the test: good or bad).

In the latter case, taking into account the experience of the inspector, the product can be assessed as good if the cross-section does not break and cracks, folds, bulges, and other similar defects cannot be detected. The object fits into the sockets of the gauge made to the appropriate tolerance (Fig. 11) [11, 12, 13]. Dimensions were verified using a CMM measuring machine and an IM-8000 digital measuring projector (Fig. 12). The measurement of the bend angle using a measuring machine showed a value of 162.552°, which indicates that it is within the assumed manufacturing tolerance of 162.5° +/- 0.3°.

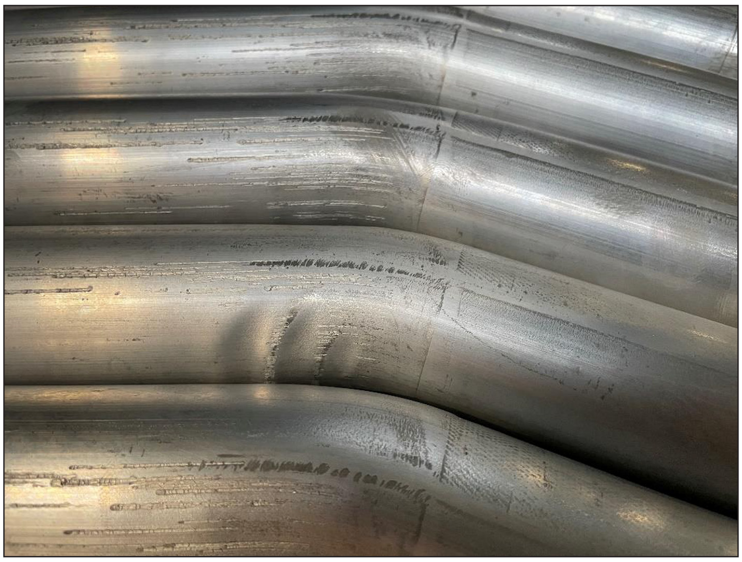

Figure 10. Forming defects in the form of folds of the inner radius

Figure 11. Verification of the geometry of the bent pipe in the device

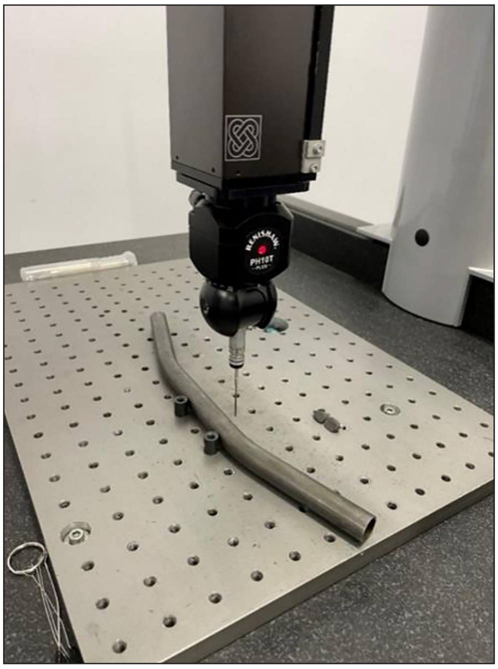

Figure 12. Measurement of pipe geometry on a CMM measuring machine

CONCLUSIONS

The tests carried out showed the limitations resulting from bending low-alloy steel pipes with high mechanical parameters. For this purpose, it is necessary to implement a research methodology in the form of FEM numerical analysis and its experimental verification, including detailed material tests. Thanks to this approach and the research methodology used (numerical simulation), significant waviness of the inner radius of the pipe was avoided. Based on the FEM numerical analysis and our own research of the bending process on a CNC 3D bending machine on pipes with diameters from D = 10 to D = 40 mm made of 1.7734.5 steel, the following conclusions were drawn:

1. Modeling using FEM and laboratory tests of the pipe forming process require the use of a practically proven numerical model.
2. FEM numerical modeling does not take into account many phenomena occurring during the actual bending process, which may cause slight deviations of the analysis from real tests and require experimental tests.
3. After the bending process is completed and removed from the tooling, the bent pipe springsdue to the elastic nature of the pipe material.
4. The main purpose of using axial tension is to eliminate folding and the problem of compressive buckling. The use of axial tension reduces compressive stresses, and as tension increases, further wrinkling can be eliminated.
5. The most common cause of plastic processing errors is the selection of too small a bending radius and cold bending of materials that are better formed under the influence of heat. High temperature at the point of deformation increases the plasticity of the material and at the same time reduces stresses that can cause permanent and irreversible damage to the material.
6. After the bending process is completed and removed from the tooling, the bent pipe springs, and the springback value depends on the type of material and the bending radius.
7. The bending method of pre-stretching the pipe allows for very precise bending. The use of a 14-axis CNC machine prevents deformations on the bent walls.
8. Failure to use a mandrel with an optimal shape and diameter in the pipe forming process may cause radial components of longitudinal bending in round pipes and stresses leading to an oval deformation of the round cross-section of the pipe, the so-called pipe ovalization.

Tests have shown that steel 1.7734.5 is difficult to form, but it is possible. Because this steel is a chrome-molybdenum-vanadium alloy steel with high strength parameters, it was necessary to determine the springback effect. The empirical determination of springback could be subject to small inaccuracies (no consideration of the bending process and boundary conditions) for this type of steel, therefore FEM numerical methods were used. Using several methods and various solvers, the springback value was determined to be approximately 5 mm. This allowed for corrections to be made when bending on a 14-axis machine. In the tests in question, the stretch bending method, which involves stretching the pipe while bending it, turned out to be the most beneficial in terms of bending accuracy and correction of the spring effect. This method allows you to get smooth and accurate shapes without damaging the material, i.e., without folds. The measurements of the geometry of the manufactured part during the control test did not reveal any irregularities. Additionally, the angle was measured on a CMM measuring machine, confirming that the profile was within the manufacturing tolerance.

As part of our own work, an alternative method of making arch profiles of truss parts was also developed; this can be used when it is not possible to shape arch elements by plastic processing.

Acknowledgments

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