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FEM SIMULATION OF MEDIUM AND LARGE DIAMETER PIPE BENDING USING LOCAL INDUCTION HEATING

Cristel MUREŞAN, Gheorghe ACHIMAŞ

Abstract: *Operation life or durability of a part is the actual period of operation until reaching limit state. Bends are the part of the fluid transport installations subject to wear, with erosion as the main cause of degradation. When flow direction is changed by means of bends, particles would not follow the fluid but would impact the bend wall, contributing to the degradation of the internal surface on the outer side of the bend. Finite element method (FEM) is the most common process of numerical analysis in engineering applications, as it provides flexibility, possibility of modelling bodies which are physically not homogenous, as well as easy implementation in general calculus programs. The object of present paper is to extend the understanding of phenomena occurring in medium and large diameter pipe bending using the mandrel pulling method with induction heating, to analyse bend wall thickness when applying different temperature ranges, and select proper lubricant for the pulling speeds in order to reduce processing time and extend the life of the mandrel profiled for erosion by ensuring constant wall thickness and a circular section, as well as to reduce manufacturing costs*

Keywords: *bends, durability, bending, numerical simulation, finite elements.*

1. INTRODUCTION

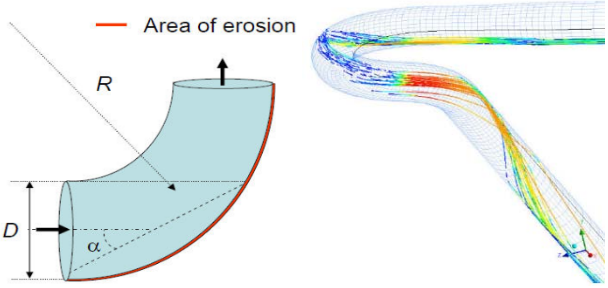
Implementing the principles of sustainable development in the industry is not only needed, but also at a good moment. Considering the importance and necessity of the three aspects of product functionality – technical, economical and ecological, the present paper identifies some directions to be followed when searching sustainable solutions for a product.

The technical-economical aspects should promote the pragmatic and immediately effective actions. The taxation and penalty system should ensure the deterrence of polluting industries and technologies and promote the so-called “clean” technologies.

“Cleaner technologies” is a concept covering multiple aspects of the economical operations as well as of the environment protection. The said concept is based on the premise that preventing is easier and cheaper than remedying after polluting the environment [2].

Bends are the parts of the fluid transport systems subject to wear, where erosion is the main degradation cause. Where flow direction is changed with bends, the particles would not follow the fluid but would impact the bend wall (see fig. 1). Generally, the interior surface on the outer bend is predisposed to erosion, but experiments indicated that for a complex isometric diagram, maximum erosion and its localization may vary [13].

It is therefore important to research the protection of internal surface of direction changing elements, against wear by friction caused by transported liquid, for the purpose of increasing durability, which would consequently increase the operation life of the entire distribution or transport network.



a) b)

Fig. 1. Fluid flow direction through bends: a) angle of impact on the bend; b) particles trajectory in a detailed isometric simulation with CFD [13]

Medium and large diameter bend manufacturing technology using mandrel curving and pulling with induction heating is the most efficient bend manufacturing method. This is the most accurate technology producing bends at 45, 60, 90 and 180° with low energy consumption, the coil can be centered and adjusted horizontally and vertically, the final product has no ovalisation, bend wall thickness is uniform, without ED (extrados) thinning or ID (intrados) thickening. Minimum radius of the mandrels is of 1.5D below 2D as provided by [20], using high advancing speed (for Dn 168.3 bends the advancing speed is of 300 mm/min), no decarburation occurs in the final product, and the oxidation is mitigated by sand blasting and protective painting.

The most important objective in the plastic deformation of metals is the production of defect free parts, with the intended mechanical and micro-structural characteristics, which can be achieved with adequate designing and proper control over the process parameters. and by knowing the behavior of materials in semi-solid state for the purpose of modeling. As regards the thixomolding, the investigation of rheological behavior of materials in semisolid state with the purpose of modeling is a domain of high interest and relevance at this moment [9].

Due to evolution of tools and devices, hot pipe bending is only used in case of large diameters, in the industry of sanitary and heating installations, as well as for transporting oil products, where for maintenance and repairs on the existing installations, all types of hot bent elbows, bends and tapers are used. According to certain authors [14], distribution networks made of steel pipes, for drinking water, heating, oil products, are classified according to ND diameter into small nominal diameters (< Dn 100 mm) and large nominal diameters (≥ Dn 100 mm).

Beneficiaries’ demands regarding the increase in quality of tubular parts, as well as the decrease of manufacturing costs, are forcing the tubular parts manufacturers to permanently improve their work technologies. On a closer look to tubular parts produced by bending with plastic deformation, they present a series of problems which should be mitigated or even eliminated.

Usual defects occurring when bending pipes are: ovalisation of cross section, wall thinning on the outer side of pipe bend, formation of creases and fissures on the inner side of pipe bend. In addition, springing occurs in particular in steel alloy pipes, eventually causing unwanted modification of bending angle and radius. Pipe resistance against interior pressure is better as much as the pipe’s cross section is circular. Thinning of the outside wall causes a decrease in pipe durability [13] [14]. Such thinning has unwanted consequences, since the inside wall of the outer side of bend is subject to wear by friction during operation, produced by fluid flowing through pipe

2. TECHNOLOGIES FOR BENDING STEEL PIPES

Pipe bending technology depends on the configuration, size and required accuracy, as well as the mechanical properties of material, production volume etc. Pipe bending can be performed with or without support, either from inside or outside. In cold state, without interior or exterior support, only the pipes with diameter below 10 mm can be bent [14].

Cold bending of pipes (cca. 20°C) with larger diameter (10 mm), in particular when the initial shape of cross section has to be maintained in the bending area, can only be performed by supporting the pipe, either from the inside or the outside.

For high production volume, it is recommended to support the pipe from the inside, in the bending area, with mandrels (fig. 2). Supporting mandrels can be spherical (fig. 2a) or spoon shaped (fig. 2b), which is the most used in practice. Such mandrel has a large contact area in the plastic deformation section of the pipe, providing good support and consequently a proper bending of the pipe. Care should be taken to periodically lubricate the supporting mandrels with a good quality lubricant.

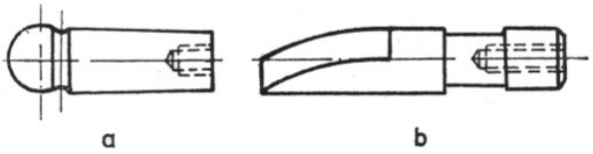


Fig. 2. Shape of supporting mandrels for pipe bending [14]

The most productive method for manufacturing pipe bends, in large quantity, is mould bending. Bends can be made by:

- bending pipes in moulds, without heating the pipe;
- hot molding, with entirely heated pipes.

Hot molding allows for bends in large diameter pipes (Dn ≥ 100 mm) and high accuracy of cross section.

Production of steel pipe bends with mandrel pulling using induction heating is the most effective method for bending large diameter pipes [16], [17]. The cinematic structure of bending equipment for 45; 60; 90; 180° is presented in fig 3 [14].

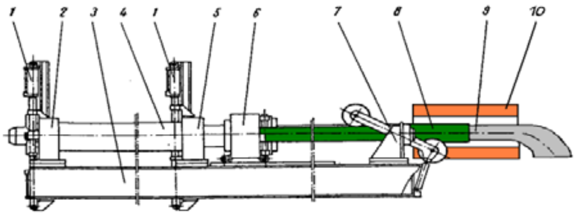


Fig. 3. Cinematic structure of bending equipment with mandrel pulling and induction heating: 1- hydraulic cylinders; 2 and 5- support bearings; 3- frame; 4- linear hydraulic motor; 6- pusher; 7- locking pawl; 8- pipe; 9- supporting mandrel; 10- heating coil

Bend manufacturing equipment using mandrel curving and pulling with induction heating using high advancing speed (for Dn 168.3 bends the advancing speed is of 300 mm/min) is presented in figure 4.

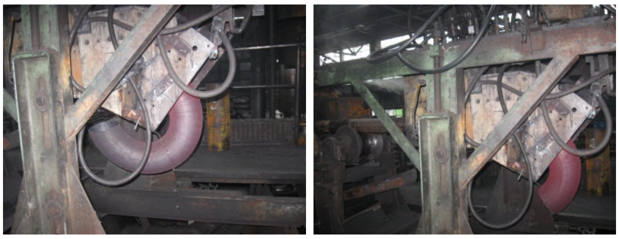


Fig. 4. Bend manufacturing by mandrel pulling and induction heating (Dn 168.3 x 4.5 mm)

The technology is extremely advantageous and effective, generating high quality bends, with low springing, minimal ovalisation, no variation of pipe thickness in bent area and no creases. The downside of this technology is the quite high cost of equipment and the wear of supporting mandrels.

A basic analysis reveals that, without requiring high accuracy, the product very well fulfils its functional purpose, as compared to similar products manufactured with other methods or technologies, the interior ovalisation is 1.0% and the exterior ovalisation is

1.50%, variation of pipe wall thickness is of 5% below the 15% measured at similar products obtained with other technologies [14].

3. NUMERIC SIMULATION OF PIPE BENDING PROCESS

3.1 Steps of problem solving using the finite element method (FEM)

The modeling of pipe bending process requires the preparation of a model for the system being studied in order to simplify the problem in question. Such simplification regards the geometry of tools, the behavior of pipe material and the limits describing the interaction between tools and pipe product.[1]

Stages of pipe bending process modeling using the Finite Element Method (FEM) are presented in figure 5.

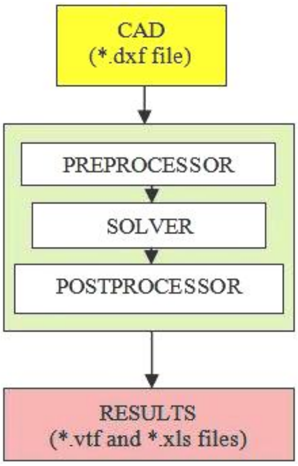


Fig. 5. Analysis procedure in Forge 2009 [5]

As per figure 5, there are:

- Pre-processing: preparation of finite element model to be transferred to the solver. In this case, the main stages are:
  - Prepare geometric model including the pipe product and pipe bending specific tools;
  - Discretisation of the pipe and tools into finite elements;
  - Define product's material properties;
  - Define contact between tools and product;
  - Determine loads and limits.
- Processing: solving of the calculation model by the FORGE 2009 solver;
- Post-processing: extract and process needed data, present results in graphic form.

Geometric modeling begins with 3D designing in Solid Works [10] of the mandrel, based on the digital processing of the original mandrel, installed at Tehnital SRL company in Ploieşti, of the German manufacturer Schmidt & Clemens GmbH as presented in 6 figure

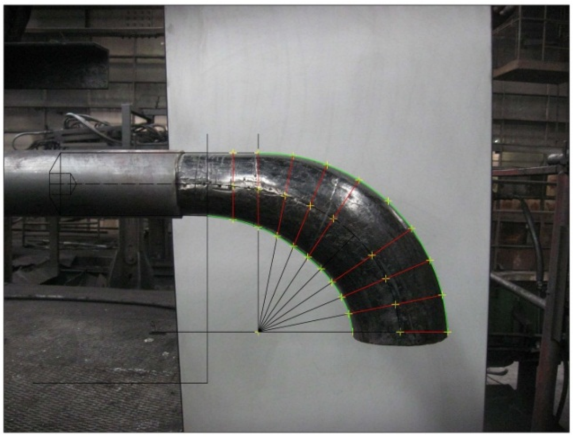


Fig. 6. Mandrel used for pipe bending with pulling and induction heating

Mandrel in figure 6 is used to perform bending of pipes with D_e 168.3 x 4.5 given the tube size D_e 114.3 x 4.5 [mm] and D_i 105.3 [mm], the other elements are designed such as to form an ensemble (see renderings in 7 figure)

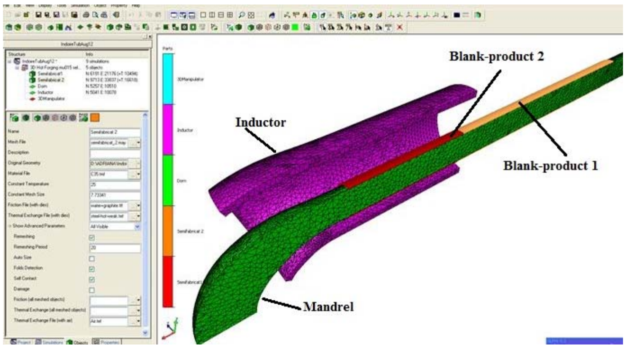


Fig. 7. Ensemble of mandrel – blank product: 1- blank product; 2- inductor, pushing system

All these sub-assemblies, together with the general ensemble were imported in FORGE 2009 and, after selecting mandrel and blank product materials, the flat discretisation was performed, followed by volumetric discretisation. For the first stage, a coarse tetrahedral mesh has been used in order to speed up calculations, as mentioned by other authors [1], [7], [8], [11]. Considering that the mesh size may influence the simulation output, in case of complex geometry such influence should be studied, given the numeric problems that might occur.

Given the structure of the bent pipe symmetrical by plane X-Y, only half of the Z axis points are being used, to reduce the number of elements. Guiding rolls are deemed to be rigid and not deformable, and the friction between rolls and pipe is ignored, to reduce the simulation time.

A file was prepared using a solid model based on a Norton – Hoff law (viscoplastic behavior).[5]

3.2 Modelling based on solid model

The Norton-Hoff model was selected for determining the parameters for the material behaviour law. Material consistency depends on thermal and mechanical conditions, which may vary, and the equation is: [5], [9]

$$A(T,\bar{\varepsilon}) = A_0 * (\bar{\varepsilon} + \bar{\varepsilon}_0)^n * e^{\frac{\beta}{T}} \quad (1)$$

where: A_0 constant; $\bar{\varepsilon}$ - cold-hardening regularisation factor; n cold-hardening exponent; β temperature factor; T temperature, in Kelvin.

When such conditions are constant, the consistency may be defined with a constant value.

3.3 Input data used for the finite element analysis

Data regarding the deformation equipment (hydraulic pushing press), deformation mould (mandrel) and blank product (pipe), as well as the conditions of the testing are fed into FORGE 2009 calculation code, following standard procedure. In the rheological module a Hansel-Spittel evolution pattern shall be considered, defined by [5], [9], [12]:

$$\sigma = A * e^{m_1 T} * T^{m_9} * \varepsilon^{m_2} * e^{m_4/\varepsilon} * (1+\varepsilon)^{m_5 T} * \\ * e^{m_7 \varepsilon} * \dot{\varepsilon}^{m_3} * \dot{\varepsilon}^{m_8 T} \quad (2)$$

where: A solid consistency [mm.Kg.s]; ε equivalent deformation (total deformation); $\dot{\varepsilon}$ - equivalent deformation velocity [s^{-1}]; T [°] temperature; $m_{1...9}$ sensitivity parameters.

Modelling may use two types of variables:
- nodal variables or internal variables (e.g. temperature, pressure, pressing speed etc.);
- integration point variables or user variables (e.g. viscosity etc.)

3.4 Friction conditions

FORGE 2009 software will use in the FEM the specific friction "τ" on the contact areas of the bodies, with equations [5], [9]:

$$\tau = \mu\sigma_n \text{ if } \mu\sigma_n < \bar{m}\frac{\sigma_0}{\sqrt{3}} \quad (3)$$

$$\tau = \bar{m}\frac{\sigma_0}{\sqrt{3}} \text{ if } \mu\sigma_n > \bar{m}\frac{\sigma_0}{\sqrt{3}} \quad (4)$$

where μ - friction coefficient, $\bar{m}$ - Tresca's friction factor.

3.5 Heat transfer conditions

Heat module – regardless of the deformation tool – material interface, the energy dissipated by friction will be included in calculation, therefore the diffusion into the rigid tool (mandrel) shall be defined. For a heat exchanging interface, the value of a constant flow (if available) should be included for determining the conduction, as well as the transfer coefficient between tool and material, and the temperature of the tool

In the thermal-mechanical calculation, the environment interface will be included as a border where complex heat exchange processes may occur as conduction-convection, radiation and constant exchange. If initial exterior temperature is not constant, the following equation shall be used [5], [12]:

$$T = (\theta_0 + 273)^{*} \exp^{\frac{\beta}{t}}, \qquad (5)$$

where: θ_0 constant; β time factor.

Thermal calculation is performed incrementally. Time step may be calculated automatically, according to variation of product's internal temperature. A maximum temperature increment may be defined, as well as a maximum time step. According to the product's internal temperature variation, the time step shall be adjusted in order to conform with the maximum temperature increment.

3.6 Discretisation

For the first stage, a coarse tetrahedral mesh may be used, in order to perform fast calculation, as mentioned by other authors [1], [7], [8], [11]. Considering the fact that the mesh size may influence the simulation results, in cases of complex geometry, the effect of mesh size should be analysed, given the numerical problems that might occur.

Under the action of tools, the semisolid material is being deformed, as well as the discretisation mesh, since FORGE 2009 approaches the forging process as a Lagrange process, which will consider the discretisation as being "material", since the mesh follows the material during its deformation (flow). Consequently, the quality of elements located in the highly deformed areas may degrade quickly. When the mesh would become too deformed, a new discretisation will be performed (automated discretisation) [4], [5], [9], [12].

Working conditions: (fig. 9, 10, 11, 12, 13)
- pushing velocity = 2.5 mm/s;
- mandrel temperature = 20 ˚C;
- heating time = 60 s;
- friction conditions – Coulomb's equation:

$\overline{m}$ = 0,15; μ = 0,15 for NS 1;
$\overline{m}$ = 0,15; μ = 0,30 for NS 2;

- heat transfer conditions for mandrel – blank product:

transfer coefficient = 4×10^4 W/m^{2}K for NS 1
transfer coefficient = 4×10^4 W/m^{2}K for NS 2
diffusion coefficient = 11763,62 Wm^{-2}K^{-1}s$^{1/2}$

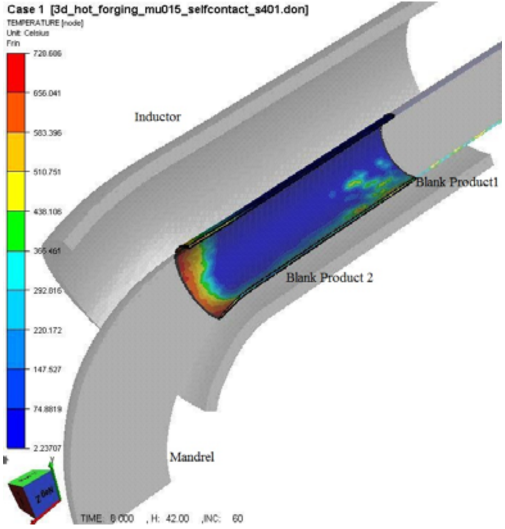


Fig. 8. Ensemble of mandrel – blank product: 1- blank product; 2- inductor, pushing system

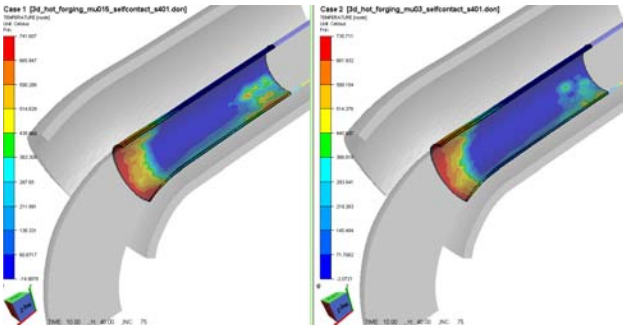


Fig. 9. Numeric simulation 1-2, μ = 0.15 Ctt = 4×10^4 left, μ=0.30 Ctt = 4×10^4 right, time 10s, increment 75.

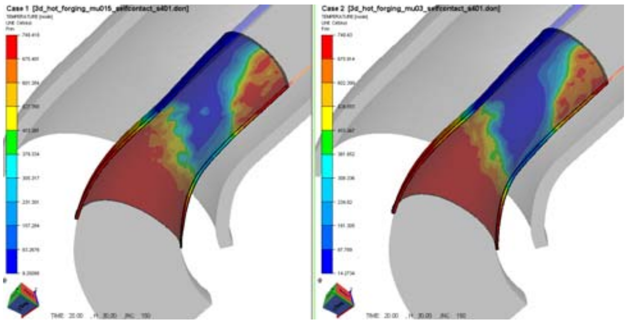


Fig. 10. Numeric simulation 1-2, μ=0.15 Ctt = 4x10^4 left, μ=0.30 Ctt = 4x10^4 right, time 20s, increment 150.

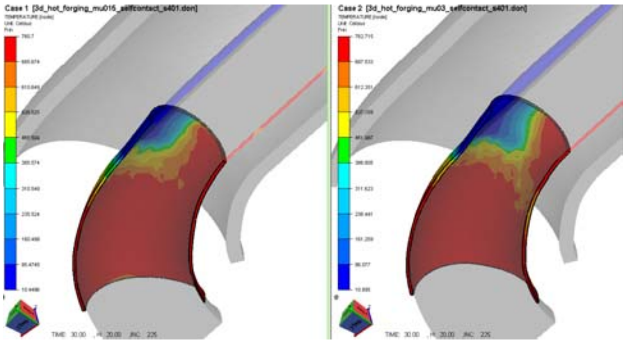


Fig. 11. Numeric simulation 1-2, μ=0.15 Ctt = 4x10^4 left, μ=0.30 Ctt = 4x10^4 right, time 30s, increment 225.

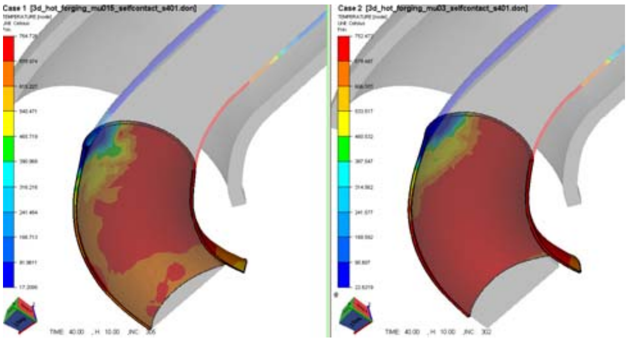


Fig. 12. Numeric simulation 1-2, μ=0.15 Ctt = 4x10^4 left, μ=0.30 Ctt = 4x10^4 right, time 40s, increment 300.

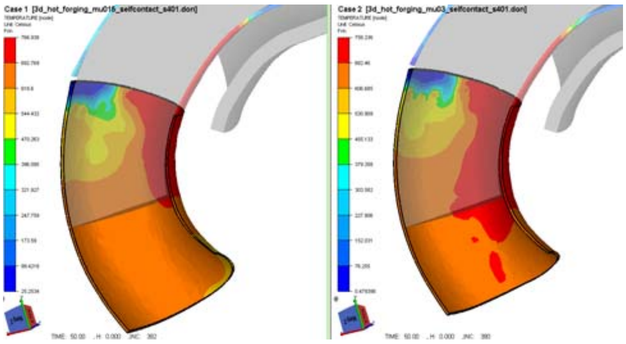


Fig. 13. Numeric simulation 1-2, μ=0.15 Ctt = 4x10^4 left, μ=0.30 Ctt = 4x10^4 right, time 50s, increment 380.

As it can be noticed, the bend wall thickness is constant and equal to the initial wall thickness, in our case 4.5 mm. Actually, under the action of the pushing system, deformation is produced in the blank product, reducing its length by compaction, with a radial redistribution of material. Initial size of the blank product was D_e 114.3x4.5 [mm] with D_i 105.3 [mm]. The blank product is being pushed over a profiled mandrel and subjected to temperature generated by electromagnetic induction in the inductor.

This application (Forge 2009) is not provided with the capability of measuring geometrical size of the bend over the whole circumference, therefore we selected a finished product for which the wall thickness was measured with mechanical and digital means, and results are presented in the following diagrams:

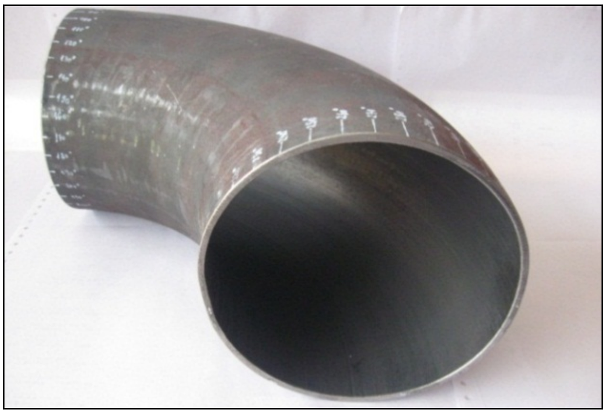


Fig. 14. Bend D_n 168.3x4.5 mm divided in 36 positions and measured.

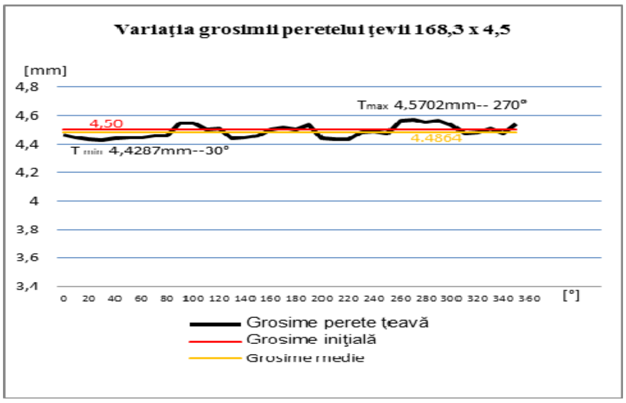


Fig. 15. Wall thickness variation for the D_n 168,3x4,5 mm bend.

We may calculate the pipe wall thickness variation with: [18]

$$\Delta T = \frac{T_{max} - T_{min}}{T_{mediu}} \cdot 100 = \frac{4{,}5702 - 4{,}4287}{4{,}4864} \cdot 100 = 3{,}15\% \qquad (6)$$

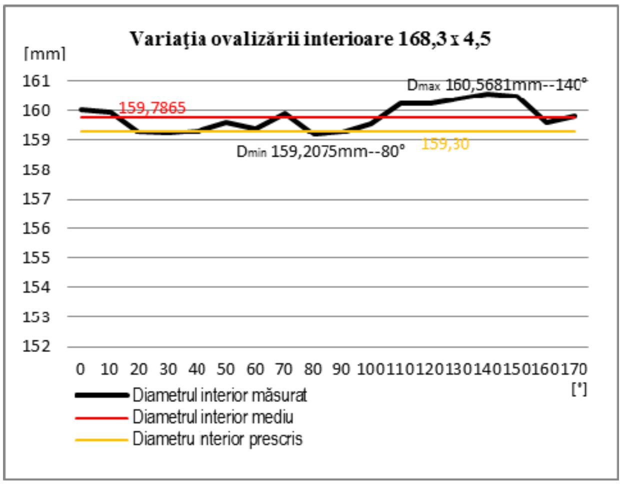


Fig. 16. Internal ovalisation variation for the D_n 168.3x4.5 mm bend.

To calculate the ovalisation on the inside of the bend we may use [18]

$$\Omega_{int} = \frac{D_{int,MAX} - D_{int,MIN}}{D_{mediu}} \cdot 100 = \frac{160{,}5681 - 159{,}2075}{159{,}7865} \cdot 100 = 0{,}85\% \qquad (7)$$

The mandrel is made in such way as to calibrate the bend interior, namely the interior ovalisation is affected by wear.

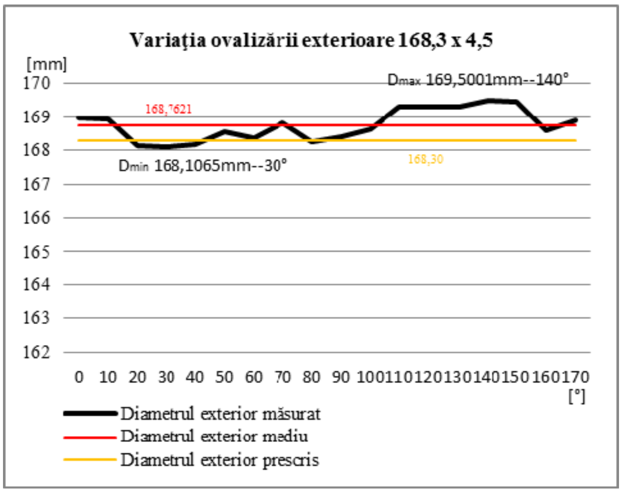


Fig. 17. External ovalisation variation for the D_n 168.3x4.5 mm bend.

As well as for external ovalisation: [18]

$$\Omega_{ext} = \frac{D_{ext,MAX} - D_{ext,MIN}}{D_{mediu}} \cdot 100 = \frac{169{,}5001 - 168{,}1065}{168{,}7621} \cdot 100 = 0{,}83\% \qquad (8)$$

5. ANALYSIS OF THE HEAT TRANSFER CONDITION'S EFFECT ON THE TEMPERATURE VARIATION ALONG THE PRODUCT'S SECTION AND ITS DEFORMATION

Working conditions: (fig. 18, 19, 20, 21)

- pushing velocity = 2.5 mm/s;
- mandrel temperature = 20 ˚C;
- heating time = 60 s;
- friction conditions – Coulomb's equation:

$\overline{m} = 0.15$; $\mu = 0.15$;

- heat transfer conditions for mandrel – blank product:

transfer coefficient = $2x10^3$ W/m^{2}K for 3.
transfer coefficient = $2x10^4$ W/m^{2}K for 4.
diffusion coefficient = 11763.62 Wm^{-2}K^{-1}s$^{1/2}$

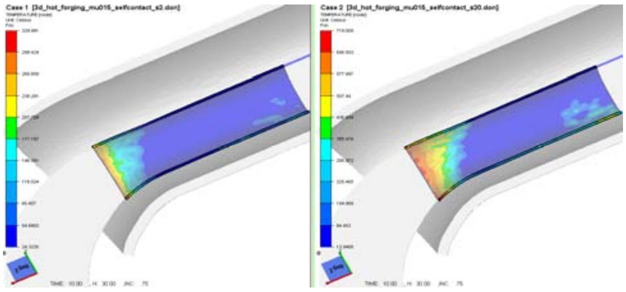


Fig. 18. Numeric simulation 3-4, μ=0.15 Ctt = $2x10^3$ left, μ=0.15 Ctt = $2x10^4$ right, time 10s, increment 75.

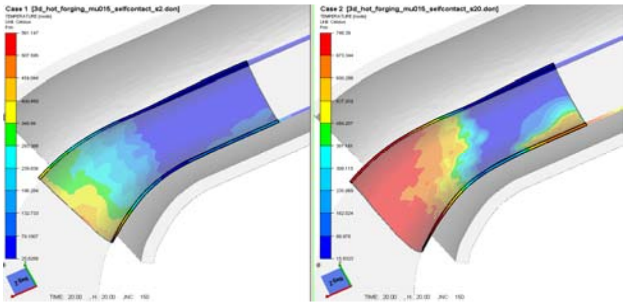


Fig. 19. Numeric simulation 3-4, μ=0.15 Ctt = $2x10^3$ left, μ=0.15 Ctt = $2x10^4$ right, time 20s, increment 150.

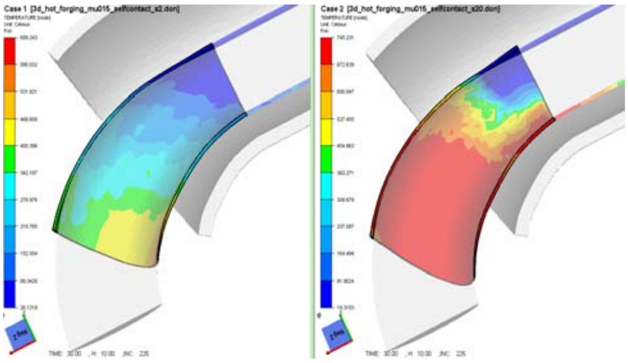


Fig. 20. Numeric simulation 3-4, μ=0.15 Ctt = 2x10^3 left, μ=0.15 Ctt = 2x10^4 right, time 30s, increment 225.

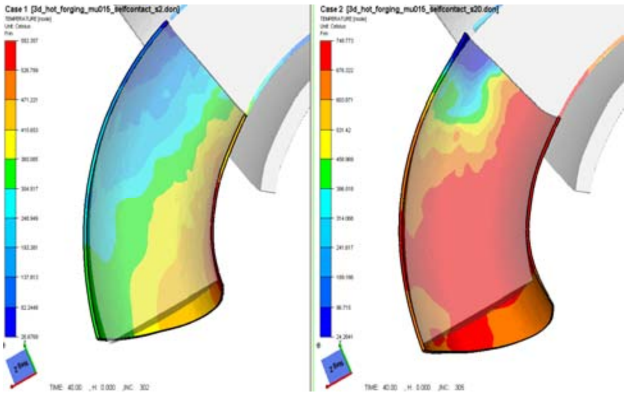


Fig. 21. Numeric simulation 3-4, μ=0.15 Ctt = 2x10^3 left, μ=0.15 Ctt = 2x10^4 right, time 40s, increment 300.

Results of these 4 numeric simulation are presented as diagrams for comparison purposes. Diagrams will present values for maximum temperature, friction and deformation of blank products.

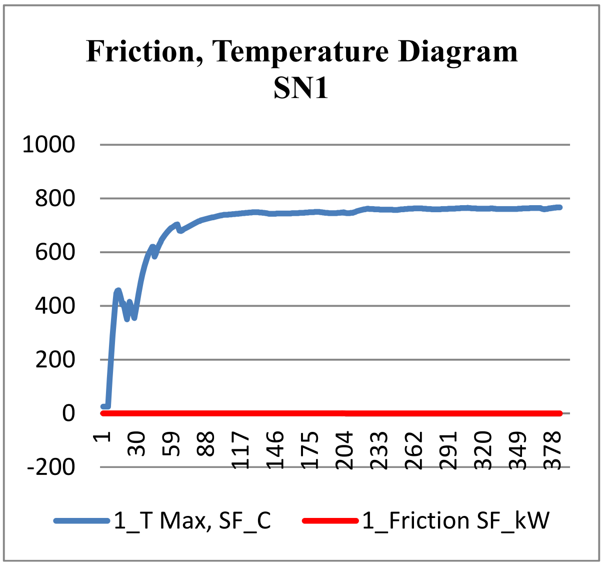


Fig. 22. Numeric simulation 1, μ=0.15 Ctt = 4x10^4

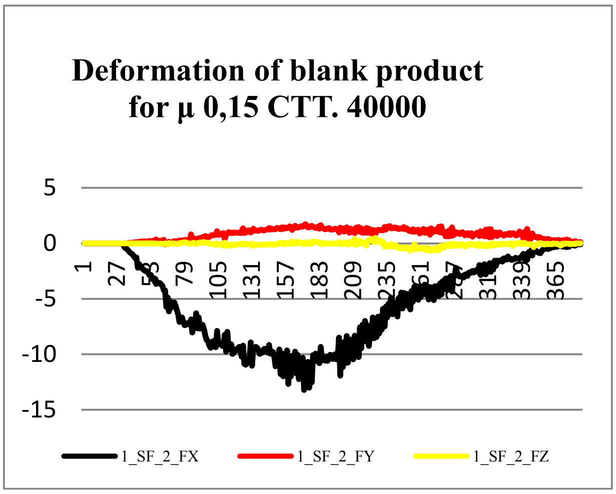


Fig. 23. Deformation of blank product, Numeric simulation 1, μ=0.15 Ctt = 4x10^4

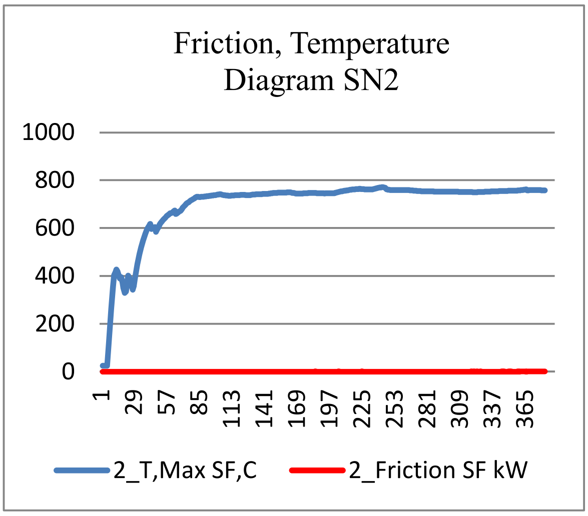


Fig. 24. Numeric simulation 2, μ=0.30 Ctt = 4x10^4

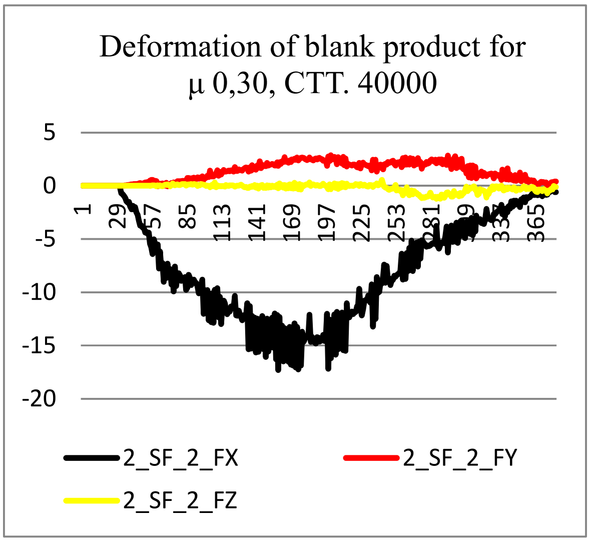


Fig. 25. Deformation of blank product, Numeric simulation 2, μ=0.30 Ctt = 4x10^4

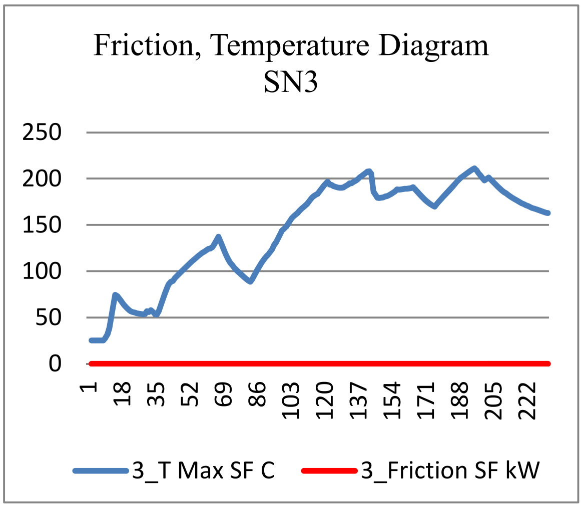


Fig. 26. Numeric simulation 3, μ=0.15 Ctt = $2x10^{3}$

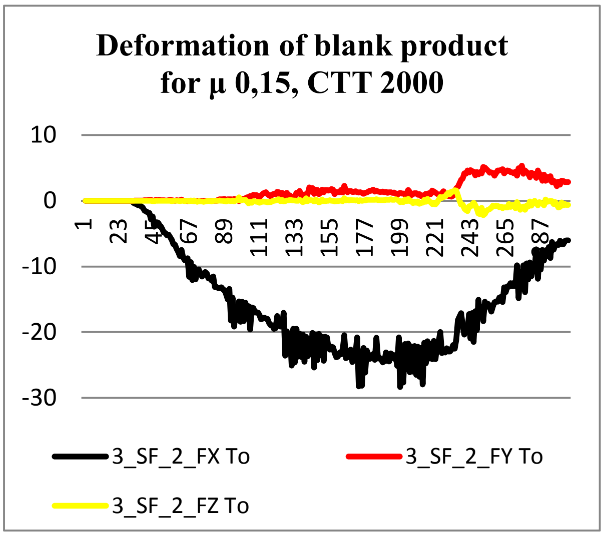


Fig. 27. Deformation of blank product, Numeric simulation 3, μ=0.15 Ctt = $2x10^{3}$

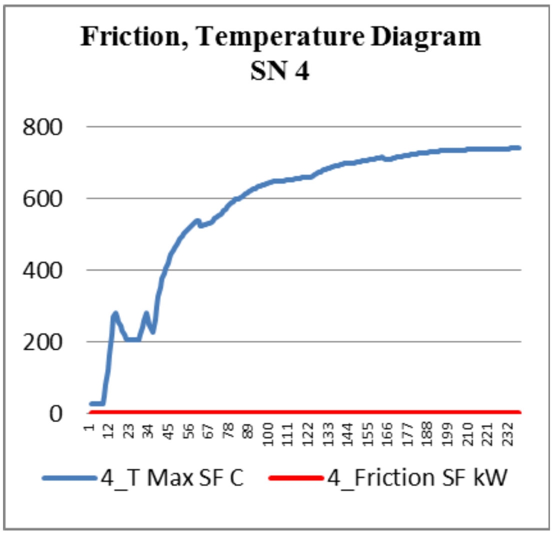


Fig. 28. Numeric simulation 4, μ=0.15 Ctt = $2x10^{4}$

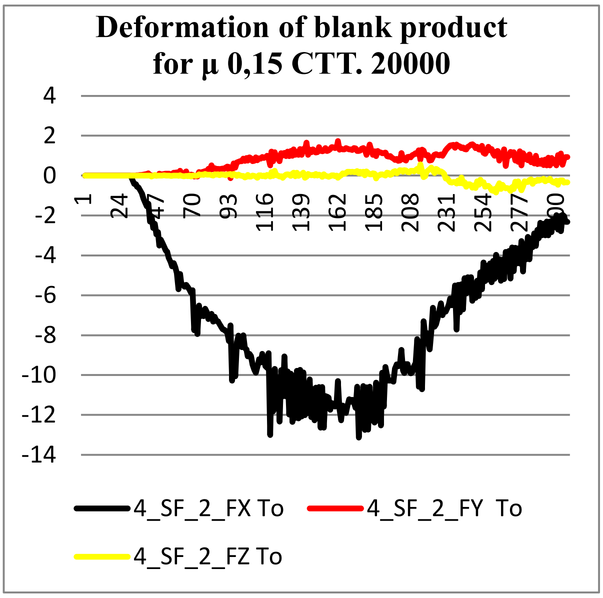


Fig. 29. Deformation of blank product, Numeric simulation 4, μ=0.15 Ctt = $2x10^{4}$

6. CONCLUSIONS

Continuously increasing demands from the beneficiaries lead to the creation of a product with numerous advantages, effective and of high quality, without the technological defects of other products manufactured by other methods, and applying the "cleaner technology" principle.

Based on the concept formulated by Avitzur [3], who stated: "As regards the plastic deformation processes, models to provide an accurate description are not yet available, however approximations and simplifications of certain techniques may be applied", we have reduced the base model due to its size and consequently the estimated completion time. All such approximations allowed for achieving the objectives stated in the first part of the paper, namely to determine the mandrel temperature and to demonstrate the lack of variation in the thickness of blank product even after processing.

As it may be noticed, the products has a constant wall thickness ($\Delta T=3.15\%$), internal ovalisation ($\Omega_{int}=0,85\%$) and external ovalisation ($\Omega_{ext}=0,83\%$) are very low, below 1%, depending on the equipment adjustments and the wear of the profiled mandrel.

In real situations, process temperature reaches about 850°C in the extrados ED and about 900°C in the intrados, the temperature variation is achieved by moving the mandrel closer or farther from the inductor. It has been proved that such distance is of 2/3 for the ED and 1/3 for the ID (fig. 9, 10, 11, 12, 13).

New technologies of bend manufacturing eliminate negative effects of defects occurring when bending pipes, such as: cross section ovalisation, wall thinning on outer side of pipe bend, formation of creases and fissures on the inner side of pipe bend, arching of bending radius. Another defect occurring during the operation is the thinning of the inside wall on the outer side of the arch, caused by friction generated by the fluid flowing through the installation.

It is important to increase the hardness of interior side in the wearing area to compensate the negative effects of friction by applying and fixating, by burning, a glass pellicle hardened with enamelling technology.

Forge 2009 application is not capable of generating differing temperatures or heating by electromagnetic induction, therefore we used a radiation heat transfer coefficient $C_{TT}=4x10^4$ W/m^2K, which combined with the friction coefficient $\mu=0,15$ in numeric simulation 1 produced best results. In [16] [17] Hu Z. Li X. used heat transfer coefficients of the order of 10^{30} which were proved to be too large.

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SIMULAREA NUMERICĂ PENTRU ÎNDOIREA ŢEVILOR DE DIAMETRE MEDII ŞI MARI UTILIZÎND INCĂLZIREA LOCALĂ PRIN INDUCŢIE

Rezumat: Durata de funcţionare sau durabilitatea unei piese, reprezintă timpul efectiv de funcţionare până ajunge la starea limită. Coturile sunt partea din instalaţiile de transport ale fluidelor care sunt supuse uzurii, eroziunea fiind principala cauză de degradare. Când direcţia de curgere a lichidului transportat se schimbă cu ajutorul coturilor, particulele nu vor urma fluidul ci vor lovi peretele curbei contribuid la degradarea suprafeţei interioare aflată la exteriorul curbei. Metoda elementelor finite (MEF) este cel mai răspândit procedeu de rezolvare numerică a metodelor inginereşti, deoarece asigură flexibilitatea, posibilitatea de a modela corpuri neomogene după proprietăţile fizice şi uşurinţa implementării în programele de calcul generale. Scopul lucrării este: cunoaşterea mai aprofundată a fenomenelor care apar la îndoirea tuburilor de diametru mediu şi mare folosind metoda tragerii pe dorn utilizând încălzirea cu curenţi de inducţie, analiza grosimii peretelui coturilor la temperaturi diferite, şi alegerea unui lubrifiant adecvat vitezei de tragere în vederea reducerii timpului tehnologic de lucru, şi creştere a durabilităţii dornului profilat la eroziune, prin fabricarea cu o grosime a peretelui constantă şi o formă cât mai apropiată de secţiune circulară, respectiv de reducere a costurilor de fabricaţie.

Cristel MUREŞAN, Phd. Student Eng., Technical University of Cluj-Napoca, Department of Manufacturing Engineering, Muncii Boulevard 103-105, Cluj-Napoca, ROMANIA, e-mail: cristelmuresan@yahoo.com; Gherla 405300, Str. Mihai Viteazu no. 25, Judeţ Cluj, 0264 243129, 0744 604794.

Gheorghe ACHIMAŞ, Prof. Dr. Eng., Technical University of Cluj-Napoca, Department of Manufacturing Engineering, Muncii Boulevard 103-105, Cluj-Napoca, ROMANIA, e-mail: Gheorghe.Achimas@tcm.utcluj.ro; Cluj-Napoca 400537, St. Clăbucet no. 1/38, Judeţ Cluj 0720 054863.