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Application of Hydroforming Process in Sheet Metal Formation

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Preliminary note

This article deals with the theory and application of a hydroforming process. Nowadays automobile manufacturers use high strength sheet metal plates. This high strength steel sheet metal plates are strain hardened in the process of metal forming. With the use of high strength steel, cars are made lightweight, which is intended for low fuel consumption because of high energy prices. Some examples of application of a hydroforming process are simulated with FEM.

Primjena postupka hidrooblikovanja u postupku oblikovanja metala deformiranjem

Prethodno priopćenje

Ovaj rad prikazuje teorijsko znanje i praktičnu primjenu postupka hidrooblikovanja metala deformiranjem. Danas proizvođači automobila koriste limove od visokočvrstih čelika. Ove ploče iz visokočvrstih čelika očvršćuju u postupku oblikovanja. S upotrebom visokočvrstih čelika, automobili su lakši, što je namjera proizvođača zbog manjeg utroška goriva zbog visokih cijena goriva. Neki primjeri primjene postupka hidrooblikovanja simulirani su metodom konačnih elemenata i prikazani u radu.

1. Introduction

A hydroforming process is a process where pressurised fluid deforms thin sheet metal plate, or pipe. Hydroforming can be free (without tool), or in a closed tool cavity. With free hydraulic forming, two pieces of sheet metal plates are cut and edge welded together. Through the flange, fluid is pumped between two welded sheet metal plates, and the part is formed. Since there is no limitation, sheet metal plates will be formed in the natural way, causing wrinkles and irregularities on part of the surface. The only way of predicting sheet metal plate formation, is by the use of Finite Element Method. This process of free hydroforming is rarely used.

Closed tool forming is used instead. It can be applied on the sheet metal plates, metal pipes and closed profiles, and also with a welded sheet metal plate as in a free hydroforming process.

In order to overcome the energy crisis and less fuel consumption, automobile manufacturers are developing lightweight automobile components. These components are made from high-strength steel (HSS). The process of forming automobile components made out from HSS, consist of two main operations – hot forming and quenching of boron steel in the water cooled tool. Materials used in the production are cold or hot rolled sheets of high strength steel (HSS), and ultra high strength steel (UHSS), with tensile strength from 600 to 1400 MPa.

These materials have increased strength, compared to mild steel, but their elongation is reduced. With reduced elongation formability is reduced as well (Figure 1). They also have more expressed effect of mechanical springback.

From the initial boron steel - sheet metal plate, made by cold or hot rolling, through the process of hot formation and quenching, the tensile strength rises from approximately 600 up to 1400 MPa, because of micro structural transformation from austenitic to 100 % martensitic structure. Micro structural transformation is achieved by quenching from approximately 920 °C, and another positive feature is that the springback is reduced in great measure with this process.

Symbols/Oznake

A	- cross sectional area, mm^2 - površina poprečnog presjeka
A_{10}	- engineering strain, % - istezanje
α_1	- angle of scope of tube, ° - kut obuhvaćanja
β	- coefficient of flatted strained state - faktor ravninske deformacije
D	- diameter, mm - promjer
d, d_u	- diameters, mm - promjeri
E	- modul of elasticity, GPa - modul elastičnosti
ε_p	- plastic portion of true strain - plastični udio stvarne deformacije
F_A	- axial force, N - aksijalna sila
F	- force, N - sila
F_e	- maximum compression end tube force, N - maksimalna tlačna sila na kraju cijevi
F_f	- opposing frictional force, N - reakcijska sila trenja
k_f	- hardening stress, MPa - naprezanje očvršćavanja
l	- length, mm - duljina
μ	- factor of friction - faktor trenja
p	- pressure, MPa - tlak
φ	- true strain - stvarna deformacija
ρ	- bending radius, mm - polumjer savijanja
R_0	- middle radius of tube, mm - središnji polumjer cijevi
R_p	- radius of bending, mm - polumjer savijanja
R_θ	- radius, mm - polumjer
R_{p02}	- yield stress, MPa - naprezanje tečenja
R_m	- ultimate tensile strength, MPa - vlačna čvrstoća
s	- tube wall thickness, mm - debljina stijenke cijevi
t	- wall thickness, mm - debljina stijenke

Also another positive feature is low carbon content, which is one of the basic requests for good welding possibilities.

After formation the parts need to be post processed by laser cutting and sanding.

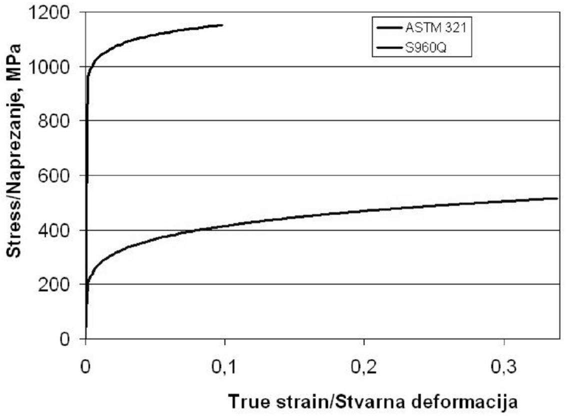

Figure 1. Stress as a function of true strain for two different materials

Slika 1. Usporedne krivulje očvršćenja za dva različita materijala

2. Hydroforming

Because of the necessity for complex tubular parts, with different cross sections in the automobile industry, the process of hydroforming is widely used. Usually the hydroformed parts are made from pipes. Often, these pipes need to be pre-bended in one ore more operations in order to approximate the shape of the final product. After these pipe – preparing operations, the process of hydroforming can be applied. This process of hydroforming is the process of applying internal pressure to the pipe (by means of fluid), which then stretches the pipe to the inner surfaces of the tool. A hydroforming process can also be with and without axial feeding at the ends of the pipe. The diameter of the pipe and cross section of the final product are correlated. If the perimeter of the cross section is larger than one directed by the pipe diameter and maximal allowed material elongation, the tube will be thinned and may fracture.

With tube pre-bending, material properties change, and the material can be strain hardened, which can affect the later process of hydroforming. Also, during hydroforming, the tube thickness changes. This change of thickness depends on the following factors: bend radius, usage of appropriate lubricants, quality of tool surface, pressure of fluid etc. Pre-bending can be done on the CNC bending machine. Hydroforming presses have different working conditions, as opposed to the hydraulic presses for conventional deep drawing. Conventional deep drawing presses need to have ram force distributed along the forming stroke of the tool. Hydroforming presses require ram force for closing the tool, which is under fluid pressure, and for the stroke of hydraulic cylinders, which is used only for compensation of the press frame elongation under loading. The maximum die closing force (ram force) during the process of hydroforming can be calculated as the product of the maximum fluid pressure and projection of die cavity onto the division line.

A hydroforming press should have a long closing stroke with small forces and high speed - for taking the products out of die, and placing new unformed sheets. Also a high die clamping force, with fast and small stroke is desired for the operation of hydroforming. High frame stiffness, and high table stiffness is desired. Also hydroforming presses should have axial cylinders installed for holding fluid pressure and applying axial feed if necessary.

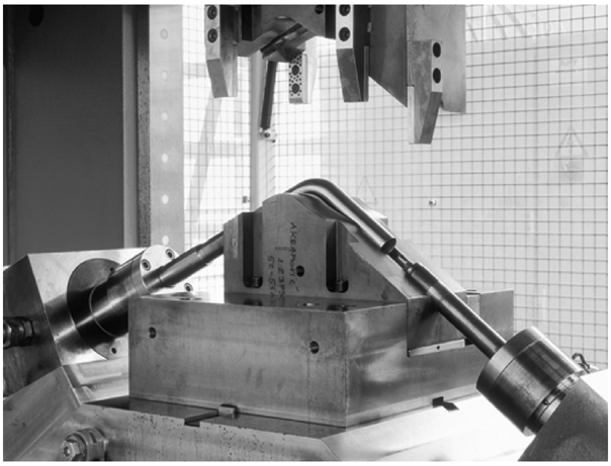

Figure 2. Hydroforming press, with axial feed cylinders [1]

Slika 2. Presa za hidrooblikovanje s aksijalnim cilindrima [1]

In the external pressure hydroforming (Figure 3), the tube is formed onto a mandrel by external hydraulic pressure, which acts between the external surface of the tube and the inner surface of a tool. On both ends, the tool is sealed against the tube.

This process enables accurate inner surface contours or the joining of the mandrel and the tube.

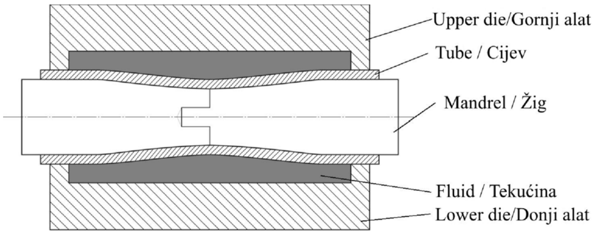

Figure 3. The concept of external pressure hydroforming

Slika 3. Princip vanjskog hidro oblikovanja

In the internal pressure hydroforming (Figures 4, 5), pressure is applied to the inner surface of the tube, which forms the tube in a such way, that it takes the shape of a die cavity.

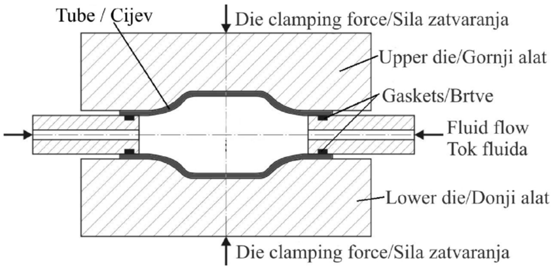

Figure 4. Hydroforming without axial feed

Slika 4. Hidro oblikovanje bez aksijalnog pomicanja

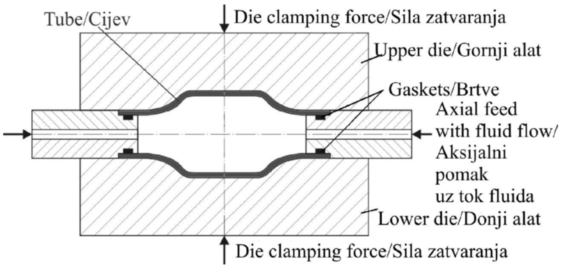

Figure 5. Hydroforming with axial feed

Slika 5. Hidro oblikovanje s aksijalnim pomicanjem

The process of tube end feeding increases formability of material. With axial feeding, there is minimal reduction of material thickness, so multi-branch components like "T" sections can be easily produced.

Axial feed requires a precise process control, and it is one of the parameters which affects the formability of some hydroformed part.

Forming limit diagram (FLD) shown in Figure 6 is used to track material changes during process of deformation, which can lead to problematic places in the die cavity where sheet metal material tends to break. These places can be predicted with FEM method also.

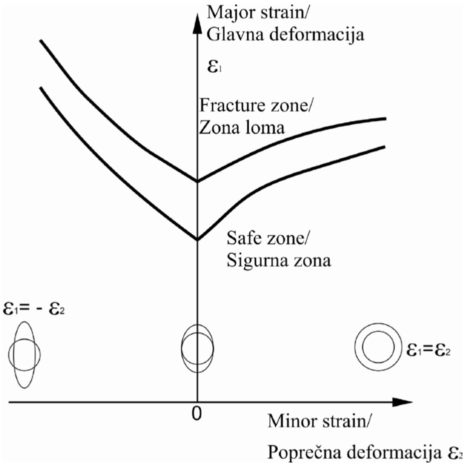

Figure 6. Forming limit diagram

Slika 6. Dijagram granične oblikovljivosti

During the hydroforming process, only a limited amount of material can be pushed into the die cavity. If too much force is exerted onto the tube, buckling will appear. The relationship between maximum compressive end tube force F_e, and the opposing frictional force F_f, friction factor μ, between the tube and die surface, length l along the tube, tube diameter D, tube wall thickness t and ultimate tensile strength R_m is [2]:

$$F_e=\pi\cdot(D-t)\cdot t\cdot R_m\text{, N} \qquad (1)$$

Frictional force F_f:

$$F_f=\pi\cdot(D-2t)\cdot l\cdot\mu\cdot p\text{, N} \qquad (2)$$

Where p, Pa is internal pressure.

Length beyond which material cannot be fed:

$$l=t\cdot R_m\cdot\frac{1-\frac{t}{D}}{\frac{(1-2t)}{D}\cdot\mu\cdot p}\text{, mm} \qquad (3)$$

One can see from the equation above, that the tube length is maximal, when the friction factor and internal pressure are minimal.

The feed pressure for round sections is approximated by [2]:

$$p=\frac{(1,7\cdot R_m\cdot t)}{(D-2t)}\text{, Pa} \qquad (4)$$

For large D/t ratios, $(D-2t)\approx D$ and ratio $\frac{1-\frac{t}{D}}{1-\frac{2t}{D}}\approx 1$. It follows that:

$l=\frac{D}{\mu\cdot 1,75}$; $l = 12\cdot D$ for $\mu = 0,05$; and $l = 6\cdot D$ for $\mu = 0,1$.

Finite element analysis (FEA) is a numerical process. The object (for example the metal tube) is approximated by finite number of elements. As the number of the elements increases – a solution is more realistic. Calculation time is much longer with the larger number of elements.

Each of these elements has numerically described material properties. When deformation of a single element is calculated according to the exerted load on the single element, the program calculates deformations of the element, and stresses in the element. Elements are connected at the nodes, so all elements that approximate some geometry, deforms under described loads. In this way, one can see calculated stresses, deformations, and other results. The finite element method is still developing in the sense of element formulation for specific problems, implementation of new calculation algorithms, and it is this area of applications which will be great in the future.

2.1. Drawing of a T-shape product

Analysing stress - strain state is estimated for four characteristic zones (Figure 7) [3-6]:

I - zone of the main tube,

II - zone of tube translating into drainage,

III - drainage zone,

IV - drainage peak zone.

$$p=\frac{\beta\cdot k\cdot s\left(\frac{1-\frac{R_0}{\rho}}{R_\rho}+\frac{1}{R_0}\right)-\frac{s\cdot R_0\cdot F_A}{R_\rho\cdot\rho\cdot A}}{1+\frac{s}{R_\rho}\left(1+\frac{R_\rho}{\rho}\right)+\frac{s}{R_\Theta}}\text{, Pa} \qquad (5)$$

where:

s, mm - tube thickness,

R_0, mm - the middle radius of tube, $R_0=\frac{d-s_0}{2}$

R_ρ, mm - radius of free bending,

R_Θ, mm - radius, $R_\Theta=\frac{\rho}{\cos\alpha_i}$

F_A, N - axial force,

α_1 - angle of scope of tube about profile ring,

A, mm^2 - tube cross sectional area,

P, mm - bending radius, $\rho > R_0$,

d, d_u, mm - inside and outside diameters of tube cross sectional area.

With increasing of force F_A to expression, the value of fluid pressure needed for tube forming is decreased.

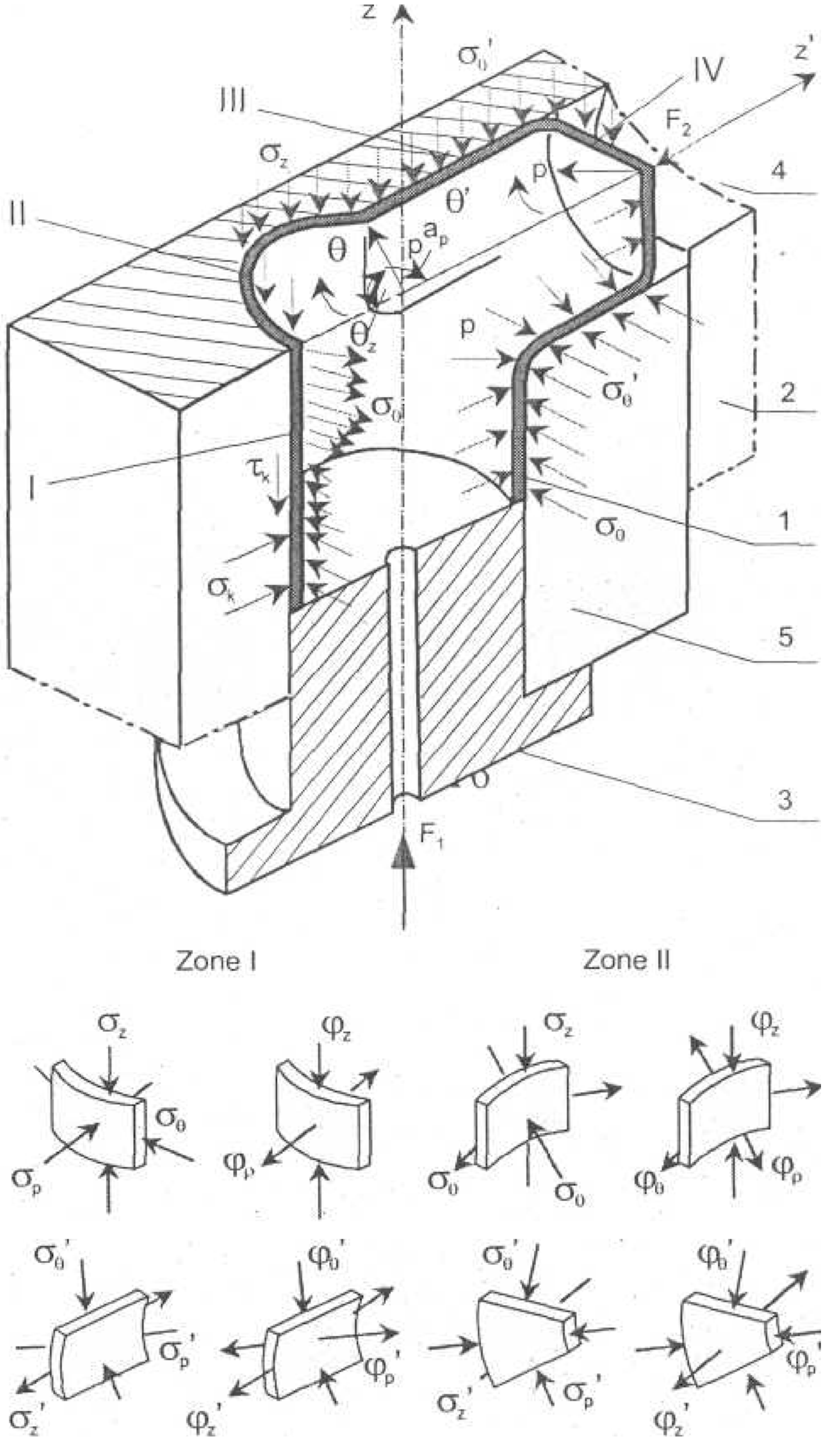

Figure 7. Scheme of stress – strain state for the T-shape product [3-6]

Slika 7. Shema naprezanja i deformacija za hidrooblikovanje T-profila [3-6]

Mathematically viewed it has the value of force F_A where $p = 0$, which means that helping force F_A formes tube without pressure acted fluid. That is not fully enabled; therefore the tube will be irregularly formed because of stability loss of tube sheet metal. The fluid pressure (p) increases with tube thickness increasing and material hardness (k).

If during the formation process pressure p = const, and for the beginning value:

$$R_0 = \rho;\ R_\rho = \infty;\ R_\Theta = \frac{\rho}{\cos\Theta} = R_0,$$

the expression for pressure takes the form of:

$$p = \beta \cdot k \frac{s}{R_0 + s}.$$

Axial force: $F_A = F_{pd} + F_{pf}$,N

where:

F_{pd}, N - force for plastic forming of tube material,

F_{pf}, N - force for pressure fluid in tube acted by press,

$$F_{pd} = \frac{\pi}{4}\left(d^2 - d_u^2\right)\left(\frac{\beta \cdot k}{2} - p\right),\ \mathrm{N}$$

$$F_{pf} = p\frac{\pi \cdot d_u^2}{4},\ \mathrm{N}$$

3. FEM simulated hydroforming process

3.1. Simulation of hydroforming alluminium 6061-T4 tube for automobile structural part

FEM simulation of hydroforming of automobile structural element - alluminium tube was performed. Pipe was modelled with shell elements, and pressure was applied on element faces as a function of time .

Mechanical properties of Al6061-T4:

Density: 2700 kg/m^3

Brinell hardness: 65

Vickers hardness: 75

Ultimate tensile strength R_m= 241 MPa

Yield strength $R_{p0,2}$= 145 MPa

Elongation A=22 %

Young modulus: 68,9 GPa

Poisson ratio: 0,33

Linear stretching factor: 23,6 μm/(m·K)

Specific heat capacity: 0,896 J/(kg·K)

Thermal conductivity 154 W/(m·K)

Strain hardening law: $k_f = 288 \cdot \varphi^{0,1105}$, MPa

Dimensions of the pipe were set as 110 mm at outer diameter, and 3 mm for pipe wall thickness.

On Figure 8, one can see upper part of the die with respective dimensions for the numeric model (Figure 9) used in the simulation.

Table 1. Chemical composition of 6061-T4 alluminium

Tablica 1. Kemijski sastav 6061-T4 aluminija

Al	95,8 ÷ 98,6 %
Cr	0,04 ÷ 0,35 %
Cu	0,15 ÷ 0,4 %
Fe	0,7 %
Mg	0,8 ÷ 1,2 %
Mn	0,15 %
Si	0,4 ÷ 0,8 %
Ti	0,15 %
Zn	0,25 %
Other elements / Drugi elementi	0,15 % total

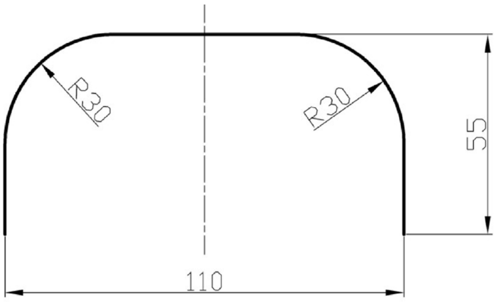

Figure 8. Drawing of the die/tool model for numerical analysis

Slika 8. Crtež gornjeg dijela alata korištenog za simulaciju

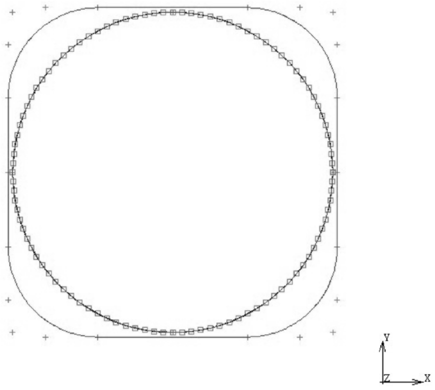

Figure 9. Numerical model with upper and lower die, and pipe model with shown nodes

Slika 9. Numerički model s prikazanim gornjim i donjim alatom, te s prikazanim konačnim elementima

Pressure on the inner surface of the alluminium pipe was set as 150 MPa, which is equivalent to 1500 bar. Simulation was conducted without axial feeding. FEM results of hydroforming of alluminium tube are shown in Figures 10, 11.

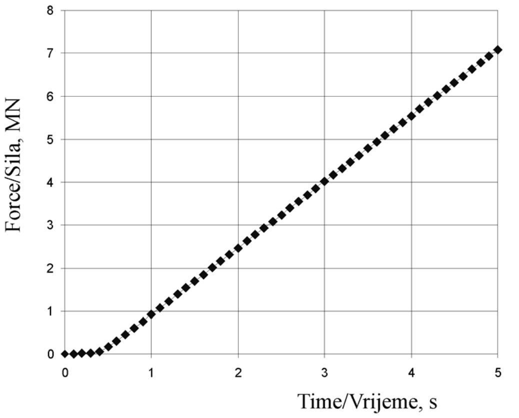

Figure 10. Force on the upper tool as a function of time

Slika 10. Sila na gornji alat u funkciji vremena

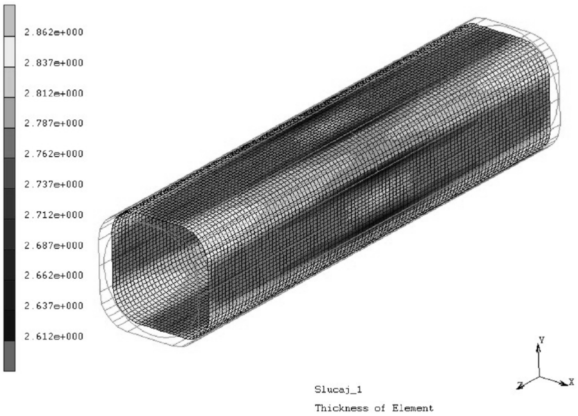

Figure 11. Element thickness of the hydroformed part

Slika 11. Debljine elemenata oblikovane cijevi

3.2. Hydroforming of circular, and rectangular below convolution

For numerical simulation, material Č4752 was chosen, according to European standard EN 1.4541.

Material properties are:

- yield strength $R_{p02} = 205$ MPa
- tensile strength $R_m = 515$ MPa
- minimum elongation $A_{min} = 40$ %.

Strain hardening can be described with function $k_f = 626{,}6 \cdot \varphi^{0{,}3365}$. Plastic portion of strain is calculated by expression $\varepsilon_p = \varphi - \dfrac{k_f}{E}$. Models used for numerical simulation are shown in Figure 12, and Figure 13. FEM results are shown in Figures 14, 15 and 16.

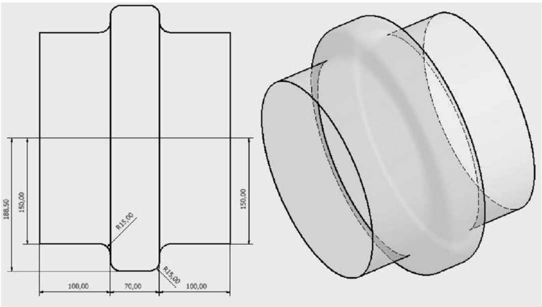

Figure 12. Model for round bellow

Slika 12. Model za okrugli kompenzator

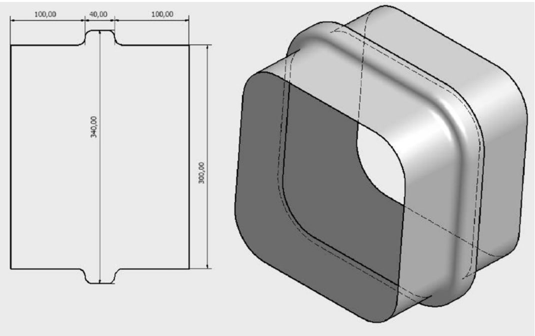

Figure 13. Model for rectangular bellow

Slika 13. Model za kvadratni kompenzator

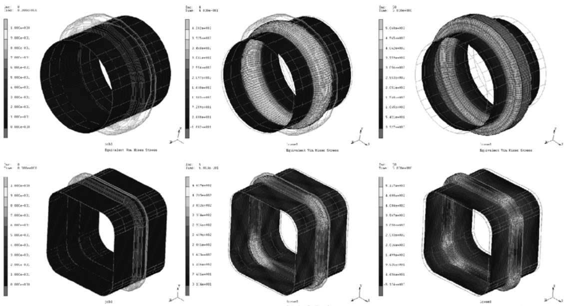

Figure 14. FEM results for different time increments

Slika 14. Rezultati MKE za različite vremenske inkremente

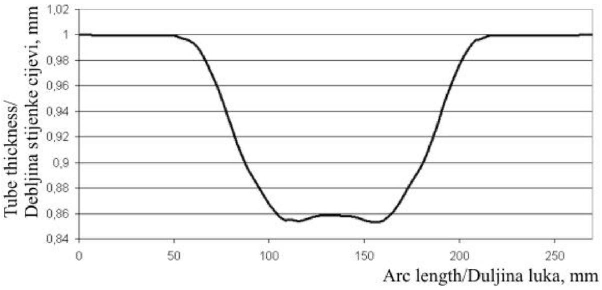

Figure 15. FEM calculated circular tube thickness at the end of the hydroforming process

Slika 15. Debljina stijenke na kraju oblikovanja – cilindrični kompenzator

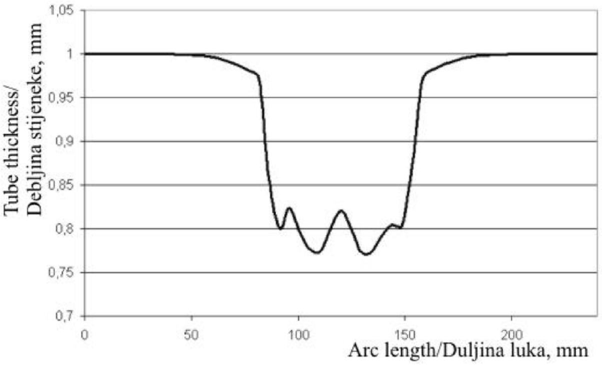

Figure 16. FEM calculated rectangular tube thickness

Slika 16. Debljina stijenke na kraju oblikovanja – kvadratni kompenzator

4. Conclusion

Hydroforming is the process of metal forming, where force is indirectly applied to workpiece by means of fluid pressure, as opposed to conventional metal forming processes. There are numerous advantages, such as possibility of production of very complex tubular parts, automatisation of hydroforming process, different tube wall thickness can be obtained with applying different working parameters such as fluid pressure, amount of axial feeding, speed of deformation etc. FEM method is used for prediction of hydroforming parameters, used during real hydroforming process. Results of FEM simulation of alluminium tube (Force on the upper tool as a function of time) make good approximation of tool closing force which was investigated in the production of automobile alluminium structural element. FEM results of hydroforming of a bellow indicated problems with the hydroforming of a rectangular bellow. This simulation was performed in order to observe change of wall thickness in shown two cases. With different hydroforming process working parameters such as fluid pressure, amount of axial feeding, speed of forming, it is possible to achieve different working conditions and product with different properties. FEM method results are used as a good starting point, which are than optimised in the real hydroforming process.

REFERENCES

[1] Akrapovič exhaust factory; "Hydroforming"; URL:http://www.akrapovic.com/technology/hydroforming, (19.05.2009)

[2] HARRY SINGH: *Hydroforming with end feeding*, TheFabricator.com, URL:http://www.thefabricator.com/Hydroforming/Hydroforming_Article.cfm?ID=122, (19.05.2009).

[3] JURKOVIĆ, M.; MAMUZIĆ, I.; KARABEGOVIĆ, E.: *The sheet metal forming with hydraulic fluid pressure*, Metalurgija 43 (2004) 4, 315-322.

[4] RANČIĆ, B.: *Sila zatvaranja alata pri oblikovanju nestišljivim fluidom delova sa bočnim odvodima,* 22. jugoslavensko savjetovanje za proizvodno mašinstvo, Ohrid 1989.

[5] RANČIĆ, B.: *Određivanje radnog pritiska i sila pri oblikovanju T-račve sa sužavanjem odvoda*, 22. jugoslavensko savjetovanje za proizvodno mašinstvo, Ohrid, 1989.

[6] STOJILJKOVIĆ, V.: *Reverzibilno izvlačenje cilindričnih elemenata nestišljivim fluidom*, Zbornik radova: Obrada deformisanjem u mašinstvu, Novi Sad, 1984, 173-185.

[7] YAMADA, Y. and TAKATSUKA K.: *Finite element analysis of nonlinear problems* // J.Jap. Soc. Tech. Plasticity, 14, (1973), 758.

[8] LARSEN, P. K.: *Large Displacement analysis of shells of revolutions, including creep, plasticity and viscoplasticity* // Ph. D. Thesis, University of California, Berkeley, 1971.

[9] MCMEEKING, M. and RICE J. R.: *Finite element formulation for problems of large elastic-plastic deformation* // Int. J. Solids Struc. 11 (1975), 601.

[10] DVOFZK, M.: *A Contribution to the Investigation of the structure of Drawn Shells Produced by the Metod of Hydromechanical Drawing*, Journal for Technology of Plasticity, 26 (2001) 1, 33 -37.