Simulation And Experimental Results Of The Hot Metal Gas Forming Technology For High Strength Steel And Stainless Steel Tubes Forming

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Abstract. Simulation is a key topic within the development of the Hot Metal Gas Forming (HMGF) technology. In this work, tube bulge tests and tubes forming processes using dies were simulated at high temperatures by means of FEM. The tube deformations calculated by the numerical simulations were compared to the results from experiments carried out at different heating conditions and using different input pressure curves. Flow curves for several stainless and high strength steels were experimentally determined in order to be used for the simulation code. Ferritic stainless steel 1.4512 showed very high formability capabilities at high temperatures. During tube bulge tests of the ferritic steel a maximum expansion of tube diameter up to 55% was reached by using a pressure of only 14 bars.

Keywords: Metal, Gas, Forming, Tube, FEM, Simulation
PACS:

INTRODUCTION

During tube Hot Metal Gas Forming (HMGF) a metal alloy tubular part is heated up. Because the yield stress of the component decreases with the increase in temperature, the part can be formed into a shape using low-pressure gas inside the tube and reducing the need for high tonnage presses, while maximum elongation can be higher than working at room temperatures.

The know-how added during the project named *TUTEMP (Plasticity At High Temperature For Forming Applications In The Automotive Industry, Project Number RFSR-CT-2004-00034* funded by the RFCS *(Research Fund for Coal and Steel)* of the *EUROPEAN COMMISSION)* is the use of this technique in order to form tubes of stainless steel and high strength steels. All these materials need temperatures around 1000ºC in order to obtain high elongation rates.

The work described in this paper includes the simulation of tube bulge tests and tube forming tests into a die. Three are the main objectives of this study: to test the formability capabilities of several steels, to establish the optimal process window for the tubes HMGF by means of simulation and to investigate the influence of the temperature field model in the principal strains results.

MATERIAL DESCRIPTION

Two stainless steels and three high strength steels were object of study within the project.

TABLE 1. Mechanical characteristics of tubes at RT

	Rp0.2 (MPa)	Rm (MPa)	A (%)
1.4301	490	705	38.5
1.4512	393	432	27.4
S355J2G4	448	528	24.2
DP600	585	728	20.0
22MnB5	431	490	20.6

TABLE 2. Chemical composition of tubes materials (values in weight %)

	C	Si	Mn	Ni	Cr	P	S	N	Al	Nb	Ti
1.4301	0.018	0.48	1.39	8.53	18.1	0.023	0.002	0.055			
1.4512	0.013	0.37	0.32	0.17	11.9	0.021	0.001	0.020			
S355J2G4	0.195	0.292	1.247			0.011	0.005	0.009	0.024	0.009	
DP600	0.123	0.367	1.423			0.018	0.001	0.004	0.023		0.009
22MnB5	0.226	0.269	1.2			0.013	0.003	0.006	0.029	0.001	0.039

Boron alloyed steels, such as USIBOR 1500 (22MnB5), have a small percentage of Boron in order to improve hardenability. The chemical composition and the mechanical properties of the investigated tube materials are illustrated in Table 1 and Table 2. The mechanical characteristics of these hot metal gas formed tubes can be very interesting.

MATERIAL FLOW CURVES

The HMGF process in steels is a brand new technology for which no theoretical or empirical know-how is nowadays available. The material behavior at high temperature must be examined for each case and the test phase development for establishing an accurate process window can take long periods of time. In order to decrease the number of laboratory HMGF tests, simulation is a key topic in these processes. Currently there is no commercial code devoted to simulate this technology. After comparing different softwares' capacities, Forge2005® code was chosen by Labein-Tecnalia for this purpose. This software is very agile and accurate for the calculation of the strain in dependency of temperature. Being HMGF a temperature depending process, the flow curves must be determined for the different materials at different temperatures and strain rates [1]. For example, in the case of the ferritic stainless steel 1.4512 (AISI 409L) cold material behaviour (between 20°C and 300ºC), the flow curves included in the code Forge2005® were used. This flow curves fulfil the Hansel-Spittel Law:

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

with the following parameters:

A = 833.7051869; m1 = -0.0011; m2 = 0.22854; m3 = 0.01042; m4 = 0.00277; m5 = 0; m6 = 0; m7 = 0; m8 = 0; m9 = 0

In order to provide input data of material properties for the HMGF simulation, experimental uniaxial hot tensile tests at different strain rates and temperatures were carried out (on the materials shown in Table 1 and Table 2) at RWTH. Five temperatures (900, 1000, 1050, 1100, 1150 °C) and four strain rates (0.00064, 0.01, 0.125, and 0.365 1 s^{-1}) were selected for the investigation, because they can cover the reasonable working range in the HMGF process. In general, it can be observed that the total elongation increases with decreasing strain rate and raising temperature. The development of stress and elongation in different test conditions was analysed in the form of flow curves. These flow curves give important material property data for the simulation of the forming process and the process window of HMGF can be consequentially determined. Figure 1 illustrates the hot tensile test procedure used in this work (1. Heating of samples at constant heating rate; 2. Samples at target temperature during a holding time of 30 seconds; 3. Tension on the samples; 4. Cooling of the samples) .

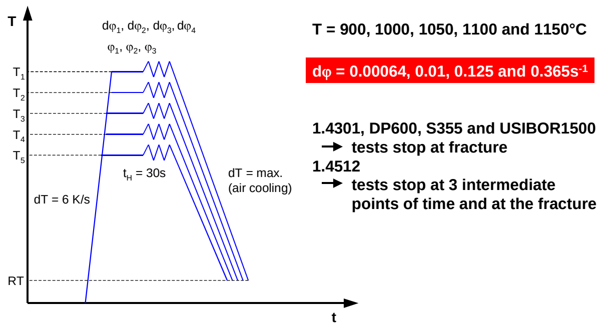


FIGURE 1. Hot tensile test program

The determined engineering stress-strain curves for all investigated materials are presented in Figure 2 for strain rates of 0.125 and 0.01 and for temperatures of 900°C and 1000°C. For steel 1.4512 the hot tensile tests at strain rate of 0.01 were not carried out up to fracture, because the specimens could be so much deformed and were not broken down. The samples were very thin, so the temperature in the gauge length became no more constant. Therefore the tensile tests for 1.4512 were then stopped before breaking in some cases. Figure 2 shows that steel 1.4512 exhibits a higher formability at both temperatures and strain rates according to the achieved engineering strains compared to the other investigated steels. The ferritic steel 1.4512 is the most interesting material for the HMGF process under these conditions and it was chosen for the experimental tests, together with the USIBOR 1500.

In the case of the ferritic stainless steel 1.4512, the determined engineering stress achieves the maximum at a very small deformation, even less than 0.05, in particular by testing at low strain rate. Therefore the flow curve evaluation for 1.4512 could be done up to small deformation values, even though steel 1.4512 in principle represents quite high deformation up to an engineering strain value of 1.

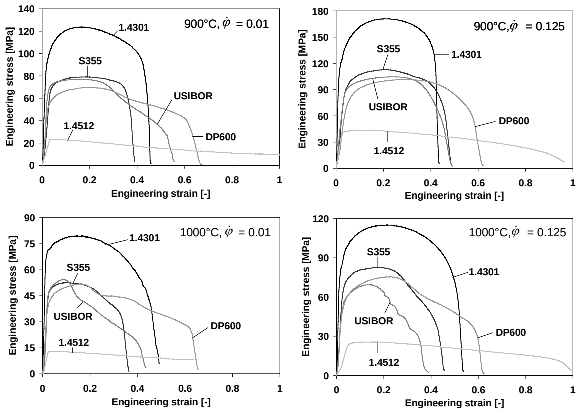


FIGURE 2. Determined engineering stress-strain curves for all investigated materials at different temperatures and strain rates

In Figure 3 the flow curves at different temperatures and strain rates obtained from the hot tensile tests for the material boron steel 22MnB5 (USIBOR 1500) are represented. These flow curves were considered in the hot tube forming simulation. It can be observed again that the flow stresses decrease when the forming temperature is increased or the deformation rate is reduced.

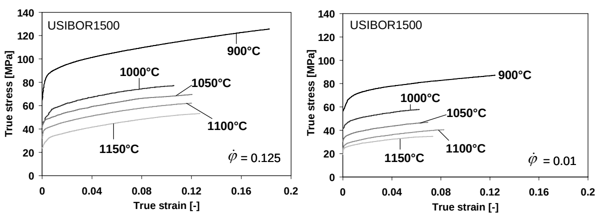


FIGURE 3. Flow curves at different temperatures and strain rates for steel USIBOR1500

Regarding the ferritic stainless steel 1.4512, in order to extend the flow curves determined in the hot tensile test, the effective cross section area of the specimens was measured during the tensile test. By means of this measured area values, the true stress could be calculated beyond the maximum loading point. In addition, hot compression tests using multi-layer specimen at different temperatures and strain rates were performed for verification of the flow curve data. From these trials it can be summarised that the flow curves determined by hot compression tests are more similar (flow stress as well as the strain hardening rate) to the flow curves from hot tensile test without consideration of the effective cross section area development. The strain hardening of the flow curves from the multi-layer compression test is nearly equal to zero after reaching the strain value of 0.2. In this case the flow curves of steel 1.4512 determined until maximum loading were extrapolated up to higher deformation with a constant stress value (strain hardening ~ 0). Figure 4 illustrates the flow curves determined from the hot tensile test together with their extrapolated curves for the steel 1.4512 at different temperatures and strain rates. These extrapolated flow curves were used to define the material properties in the simulation.

As a general conclusion, the flow curves determined by hot tensile tests at the temperatures of 900ºC, 1000ºC, 1050ºC, 1100ºC and 1150ºC were introduced in the Forge2005® code and then adjusted to the following law:

$$\sigma = K * \varepsilon^{n} * (d\varepsilon/dt)^{m} \quad (2)$$

Different K, n and m values were calculated for each temperature.

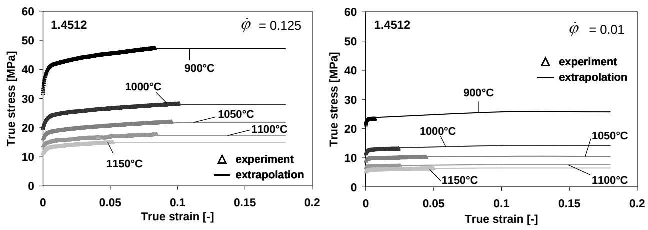


FIGURE 4. Flow curves at different temperatures and strain rates for steel 1.4512

SIMULATION

For simulating tube forming processes of stainless steels and HSS (high strength steels), the software Forge2005® was used. This is an implicit 3D code which allows coupled thermo-mechanical analysis. Three symmetry planes were considered in the part, so the model was reduced to an eighth part of the real tube.

The initial dimensions for the simulated and experimentally tested ferritic stainless steel 1.4512 and steel 22MnB5 tubes were the following ones:

- Tube external diameter: 40 mm
- Tube thickness: 1,4 mm
- Tube length: 500 mm

Modeling Of Hot Tube Free Bulge Tests

In this first case, the hot tube was freely expanded without the use of dies. Experimental tests were carried out heating the tube by Joule effect using electrical jaws. These jaws were placed at a distance of 250 mm for the 1.4512 tubes and at 140 mm for the

22MnB5 tubes, in order to obtain different deformation shapes.

In order to maintain the low yield stress of the material during the whole process, it was decided to keep the tube at high temperature even during the pressure input. Therefore electrical current was flowing through the tube until the end of the process and a temperature control system made possible to keep it constant.

The real temperatures were recorded during the experimental tests by means of thermocouples. These records were used in order to model the temperature in the tube before expansion. Figure 5 shows the FE model used for the hot tube bulge test simulation and the initial temperature on the tube. No thermal calculation was taken into account during the simulation, because the temperature was kept constant as previously explained.

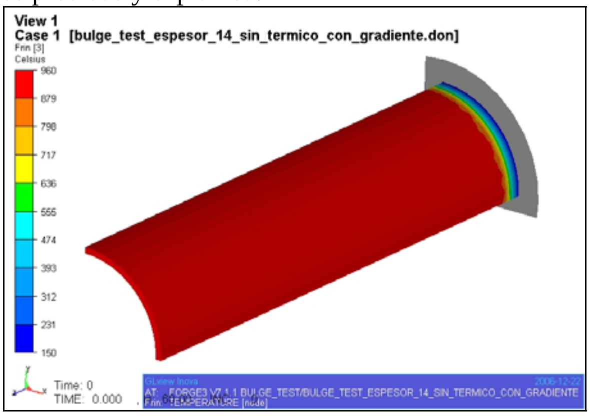


FIGURE 5. Modeling of bulge test (initial temperature)

Regarding the pressure-time curve, an initial estimation was done and after a first test phase, the experimental data obtained were introduced point by point in the software. Several simulations at different initial temperatures and using different pressure curves were performed.

Because the yield stress of the component decreases with the increase in temperature, the part can be formed into a shape using very low-pressure gas inside [2]. In the case of the tubes made in ferritic stainless steel 1.4512, the maximal internal pressure needed in order to reach 55% cross section enlargement was 14,75 bars, reached in a time of 3,75 seconds and then maintained constant. The formed tube showed a high thinning in the centre of the part. In Figure 6 the thickness distribution in the HMGF tube at the end of the process is shown.

In the case of the steel 22MnB5 tubes, bulge tests were simulated at temperatures up to 1150ºC and pressures up to 30 bars. Both experimental and simulation results showed lower formability capabilities of this material, as already stated in the flow curves results.

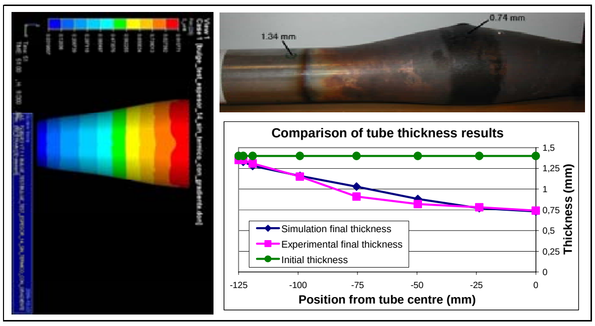


FIGURE 6. Simulation results (left), tests results (top right) and thickness distribution (bottom right) for 1.4512 tube

Modeling Of Hot Tube Expansion Tests With Dies

After validating in the laboratory the tube bulge test models, the next step was the simulation of tube HMGF with dies. Taking into account the satisfactory forming results of the ferritic stainless steel 1.4512 tubes, it was decided to perform some simulations with dies on this material.

The initial tube geometry was identical to the one used in the hot tube bulge test. The tube should be expanded in order to fill a die with 25% bigger cross section area, which included sharp chamfers. The filling of these corners was the main difficulty for achieving the final geometry.

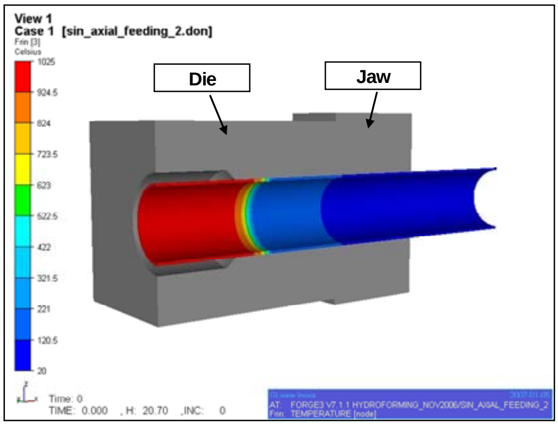


FIGURE 7. Modeling of HMGF process with dies (temperature)

Jaws and die were modeled as rigid elements at the temperature of 20ºC (no thermal calculation on them). However, the tube contact with the die had a significant influence on the different temperatures obtained along the tube (longitudinal temperature gradient) during the heating process, even before the expansion. This temperature gradient had to be considered and it was modelled according to experimental thermocouple records.

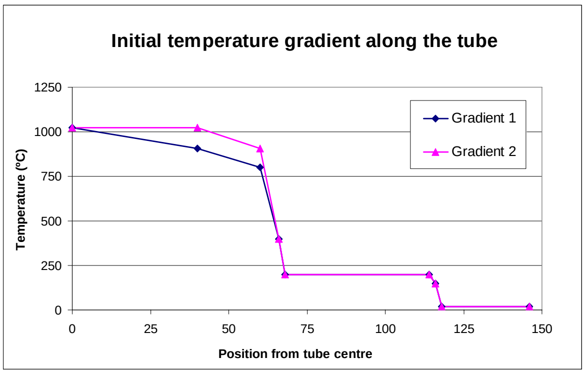


FIGURE 8. Modeling of temperature distributions before tube expansion

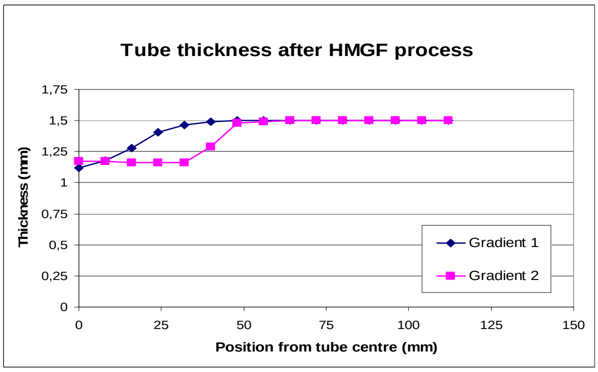
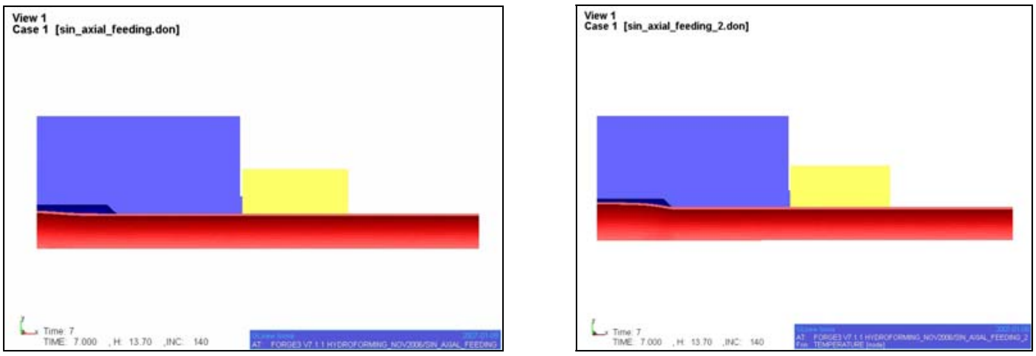


FIGURE 9. Results of thickness distribution along the tube after simulation of HMGF process

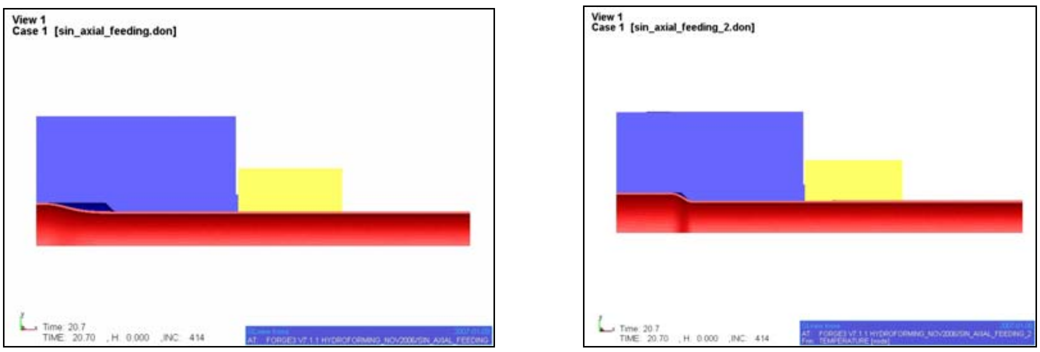
The FE model of the HMGF process with dies and the temperature gradient on the tube is illustrated in Figure 7. Different pressure-time curves and initial (before gas input) temperature distributions were applied in the simulation of the ferritic stainless steel 1.4512 tubes. Figure 8 shows two initial temperature distributions named Gradient 1 and Gradient 2 used in the simulation.

Figures 9 and 10 illustrate the thickness along the tube at the end of the simulation and the forming status during the tube HMGF process for the two cases ('Gradient 1' and 'Gradient 2').

Both cases were simulated at a maximum internal pressure value of only 14.89 bars inserted in 5.36 seconds (and then maintained constant).



Case 'Gradient 1' (left) and 'Gradient 2' (right): Situation at t = 7 sec



Case 'Gradient 1' (left) and 'Gradient 2' (right): Situation at the end of the process

FIGURE 10. Forming status during tube HMGF process simulation

Depending on the initial temperature in the central forming area of the tube, the final deformation achieved was different (see die filling in Figure 10), as well as the part thickness. The maximum thinning (22%) takes place in the middle of the tube. This thinning could be reduced by feeding material in the axial direction [3].

CONCLUSIONS

The Hot Metal Gas Forming (HMGF) process of a stainless steel tube is studied in this paper, as well as the deformation possibility for other materials. The effects of temperature gradient (on the tube length) and pressure input rate on the final shape are analyzed. The conclusions are the following ones:

1. Comparing the deformation capability of several high strength steels and stainless steels, the ferritic stainless steel 1.4512 presents the optimal characteristics for the HMGF process. Using no material axial feeding and with a minimal pressure of 15 bars, the tube bulge tests at a temperature of 960ºC show fracture after reaching a maximal diameter increase of 55%.
2. The results of experiments and simulations considering temperature, pressure measured within the tube and principal strains showed a good agreement. Therefore the code and the model used in the simulation were adjusted correctly to the real parameters.
3. Studying the deformation against a cylindrical die with 25% diameter increase, the main difficulty of the process is that of filling the die chamfers. According to simulation and experimental results, the tube thickness thinning obtained after HMGF test is acceptable, but a further material feeding [4] would reduce this thinning and a calibrated final geometry of the part would be reached in this way.
4. If the temperature gradient along the tube is not estimated accurately, material model results lose accuracy. Different temperature gradients were simulated, and the results of the experimental tests were afterwards reloaded in the simulation code in order to adjust the model.

FUTURE WORK

The next steps in the development of the HMGF technology within the framework of the project are the simulation and experimental tests of tubes HMGF with dies using material axial feeding. The optimal process window will be defined. In order to achieve this goal, the semi-industrial HMGF installation illustrated in Figure 11 will be set-up at Labein-Tecnalia.

FIGURE 11. Semi-industrial tube HMGF installation

ACKNOWLEDGMENTS

This work has been carried out with a financial grant from the *Research Fund for Coal and Steel* of the *European Community* within its *Research Programme* (Research Project *Plasticity At High Temperature For Forming Applications In The Automotive Industry;* Contract Number *RFSR-CT-2004-00034*). The authors would like to take this opportunity to express their sincere appreciation.

This project has been carried out also in cooperation with Centro Sviluppo Materiali (Italy), Acerinox, S.A., (Spain), Holding de Gestión de Empresas de Tubo, S.L. (Spain) and TNO (Holland).

REFERENCES

1. M. Merklein, J. Lechler, M. Geiger, M. Kleiner, H. Karbasian, W. Homberg, "Analysis of Thermomechanical Flow Properties of Boron-Manganese Alloy Steels", 2nd International Conference on Accuracy in Forming Technology, ICAFT 2006, Chemnitz, Germany, pp. 215-233.
2. B. Dykstra, "Hot Metal Gas Forming for Manufacturing Vehicle Structural Components", Metalforming, Sept. 2001, pp. 50.
3. S.J. Yuan, W.J. Yuan, Z.R. Wang, "Numerical Simulation of Hydroforming a Double Conical Tube", Proceedings of the 6th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes, Detroit, MI, U.S.A., 2005, pp. 595-600.
4. http://www.heatform-schuler.com/heatforming.html (2007-01-12)