Material Forming - ESAFORM 2024 Materials Research Forum LLC
Materials Research Proceedings 41 (2024) 1299-1308 https://doi.org/10.21741/9781644903131-144

Study on the influence of process parameters on the damage appearance during the push bench elongator process of super Cr13 tubes

GARCÍA GIL Eduardo[1,a *], AGHAJANI DERAZKOLA Hamed[1,b], MURILLO-MARRODÁN Alberto[1,c], and BARCO ATUTXA Jon[2,d]

[1]Department of Mechanics, Design and Industrial Management, University of Deusto, 48007 Bilbao, Spain

[2]Full Tubos Reunidos Group, Barrio, Sagarribai Kalea, s/n, 01470 Amurrio, Álava, Spain

[a]e.garcia@deusto.es, [b]h.aghajani@deusto.es, [c]alberto.murillo@deusto.es, [d] jbarco@tubosreunidosgroup.com

Keywords: Hot Working, Martensitic Stainless Steel, Ductile Damage, FEM

Abstract. In this paper the hot forming of Super Cr 13 seamless tubes during push bench elongator process is analyzed by means of laboratory experimental study and Finite Element simulation. The objective is to understand the effect of the industrial process parameters on the tube quality and the risk of damage appearance. The results of a hot tensile test campaign have been used to characterize rheological behavior of the material under the hot working conditions, and for determining the critical constants for several damage laws: Latham & Cockcroft. Finally, a Finite Element Model, FEM, of the Push Bench Elongator process have been implemented and the effect of rollers geometry and friction coefficient on tube quality and damage appearance have been addressed.

Introduction

In the Push Bench Elongator a hollow bloom, previously pierced in a Diescher Piercing Mill, is stretched by an inner mandrel which pulls from the head of the tube through several boxes of no driven rolls. As a consequence, the thickness of the tube is reduced, and its length is increased up to seven times its initial size. To meet the strict dimensional requirements the tube is finally rolled in the Sizing Mill. It is a complex process involving high temperatures and strain rates. The difficulty of the process is increased when high-performance materials are used for the tube, like the Super Cr 13 Martensitic Stainless Steels, MSS. This material, with higher resistance limit the productivity of the process due to its poor hot workability [1].

To improve process productivity and tube quality both, analytical and numerical models have been developed. Initial contributions were focussed on the flow of the material through the rolls and to improve process accuracy, mainly by analytical means. One of the first computational analysis was developed by Reggio et al. [2] and it analysed the heat transfer in the plug during the piercing process. Regarding the stretching of the tube in mandrel mills Yamane et al. [3] developed a numerical analysis of the seamless pipe process. In the paper, two of the main technical problems of mandrel mill are presented: necking and perforation of the tube wall, and "underfill". The second phenomenon is deeply analysed, however, the former one, which involves material discontinuities is not. In fact, it is a defect typical of high alloy and Stainless Steels due to the different circumferential deformation states when passing below the rolls. More recent work deal with different and relevant aspects of the process but do not cover the problem of damage. Langbauer et al.[4] developed a mathematical model to predict the temperature distribution within the pipe cross section during the hot rolling process. With this model authors can predict the temperature of the material during the process to gain control on the final microstructure of the

Materials Research Proceedings 41 (2024) 1299-1308 https://doi.org/10.21741/9781644903131-144

material. The reducing rate distribution between stands is a topic repeatedly studied, Hu et al. [5] proposed a correction theory supported by FEM simulation and experimentation providing a new method for the definition of the reduction rate. The profile of the rolls gives a wide margin to improve the process as it is shown by Wey and Wu [6].

The perforation of the wall is an important problem in the hot rolling of seamless tubes, especially for stainless steels. The relevance of this defect was already highlighted in 2015 [3] but it has not been analysed in detail up to the moment. Consequently, in this paper a damage law is developed for the Super Cr13 MSS and implemented in a FEM of the Push Bench Elongator process to understand the effect of process parameters on the material flow and product quality. For that purpose, a hot tensile test campaign of Super Cr13 has been developed, with the flow curves obtained from the tests a rheological material behaviour law was developed. Additionally, the tension tests have been simulated using the constitutive law obtained and the models are used to adjust the critical damage values of the selected ductile fracture criterion, Latham & Cockcroft. Finally, a FEM of the Push Bench Elongator process of Super Cr 13 pipes has been implanted using experimental results to study the effect of process parameters such us friction, and ovality of the roll profile on pipe quality and integrity.

Materials and Methods

Most of the works dealing with the simulation of hot forming processes use hot compression tests for the definition of the material constitutive law. In addition, for the study of damage, supplementary experimental tests are conducted in many cases. Pater and Gontarz [7], used hot compression tests for the definition of the material constitutive law, and hot tensile tests with pre-notched specimens for determining the damage criteria parameters. Muregesan and Jung [8] performed hot tensile tests with plane specimens for material characterization, and hot tensile test with pre-notched cylindrical specimens for damage model definition. By contrast, some other authors used solely hot tensile test for the definition of both, the material behaviour law and the damage criteria [9, 10]. During the stretch of the tube in the Push Bench Elongator the material is subjected to a combined state of stresses in which longitudinal tension loads have a primary role. In addition, the hole defect arisen during this kind of processes responds to tensile deformation of material [3]. Thus, for this study the results of the tension tests presented in [1] are used for the definition of both, the material constitutive law and the damage criteria. This experimental campaign consists of hot tensile test on Super Cr 13 MSS samples according to ASTME 21-09 and ASTME 08M-E04 standards. The composition of the alloy is shown in Table 1. The tested conditions are 900, 1000, and 1100 ºC and strain rates of 0.01, 0.1, 1, and 10 s-1, and the measured parameters were the load, the elongation and the temperature.

Table 1. Chemical composition and weight percentages of the super Cr 13 MSS samples tested.

Element	**C**	**Cr**	**Ni**	**Mn**	**Si**	**Mo**	**P**	**S**	**Ti**	**V**	**Fe**
Wt.%	0.03	11.5 to 13.5	4.5 to 6.5	0.5	0.5	1.5 to 3	0.02	0.005	0.01 to 0.5	0.5	Balance

Hot Tensile Behavior

From the results of the tensile tests the stress-strain flow curves, shown in Fig. 1 have been obtained. As expected, results show a decrease in material resistance to flow with increasing temperature being the case of 0.1 s-1 the one with higher peak stress values: 195 MPa, 94 MPa and 72 MPa for 900 ºC, 1000 ºC, and 1100ºC, respectively. The effect of strain rate on the material response does not follow a common trend (higher stress for higher strain rates), a fact due to recrystallization and precipitation phenomena deeply analysed in [1].

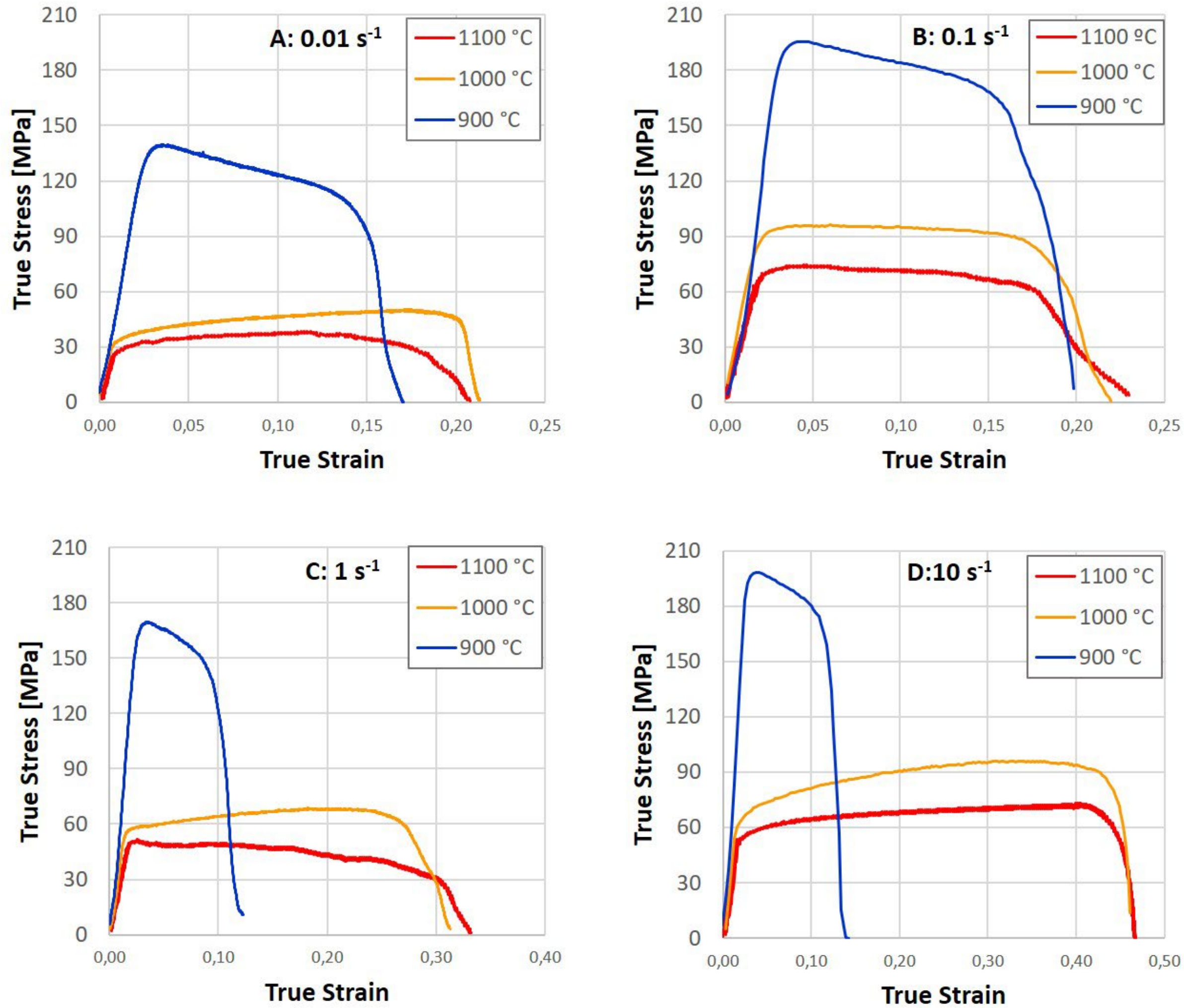

Fig. 1. Stress-Strain flow Curves of the hot tensile test of Super Cr 13 MSS at different strain rates: (A) 0.01 s^{-1}, (B) 0.1 s^{-1}, (C) 1 s^{-1}, (D) 10s^{-1}.

These curves have been used for obtaining the function parameters describing the relationship between the flow stresses and the strain. In this case, the Hansel-Spittel constitutive model has been selected, according to Eq.1:

$$\sigma = A \cdot e^{m1T} \cdot \varepsilon^{m2} \cdot \dot{\varepsilon}^{m3} \cdot e^{\frac{m4}{\varepsilon}}, \tag{1}$$

Where A, m1, m2, m3, m4 are the coefficients of the constitutive equation, which have to be defined, and T is the temperature, ε is the strain and $\dot{\varepsilon}$ is the strain rate. The coefficients A, m1, m2, m3, m4 have been determined by the Generalized Reduced Gradient (GRG2) optimization method implemented into Microsoft Excel. The optimized function for the determination of he coefficients was the quadratic error function. As a result of the optimization the parameters gathered in table 2 have been obtained. This material behaviour law has been implemented in Forge NxT 4.0 for the development of the models.

Materials Research Proceedings 41 (2024) 1299-1308 https://doi.org/10.21741/9781644903131-144

Table 2. Hansel-Spittel Coefficients obtained for Super Cr 13 MSS

A	188397.6621
m1	-0.007936329
m2	-0.088440714
m3	0.062890826
m4	-0.006544786

Calculation of Ductile Fracture Damage Criterion

During the deformation processes the limit of the material can be reached leading to the fracture of the material. The occurrence of ductile fracture during metal forming is related to modifications on microstructure, stress and strain states. Damage models relate the evolution of theses variables with the development of damage in the material, and are usually described following an equation of the form shown below (2):

$$\int_0^{\varepsilon_f} f(\sigma) d\varepsilon = C, \tag{2}$$

where $f(\sigma)$ is a function describing the variation of stress as a function of strain, ε_f is the strain limit, and *C* is the critical value of the damage criteria, at which the fracture occurs. In this study, the widely spread Latham & Cockroft criterion is be used. It uses the following expression to compute damage:

$$\int_0^{\varepsilon_f} \left(\frac{\sigma_1}{\sigma_i}\right) d\varepsilon = C, \tag{3}$$

Where σ_1 is the first principal stress, and σ_i is the effective stress. These parameters cannot be evaluated directly in the tensile test, because they are not constant during deformation, are strain dependant. Therefore, *C* is computed with the aid of FEM models developed in Forge NxT 4.0. The procedure is as follows: a 3D FEM model reproducing the parameters of the tension tests is created for each of the combination of tested conditions. According to the tested conditions, a total of 12 models have been created. For each model, the fracture damage parameters at the fracture strain are obtained giving as a result the *C* parameter for each condition. The limit strain has been obtained from the strain-stress graphs shown in Fig. 1.

The model consists of two rigid dies attached to the sample, which has plastic behaviour according to the Hansel-Spittel law with the coefficients of Table 2. The sample is meshed using 3D tetrahedral P1+linear elements with a bubble node with a generic size of 2 mm which is refined in the mid-section to 0.4 mm size, see Fig. 2A. The rest of the parameters are adjusted to reproduce test conditions of strain rate and temperature. The figure shows as well the results for the case of 1000ºC and 0.01s-1 of equivalent strain (B), first principal stress (C), and strain rate (D).

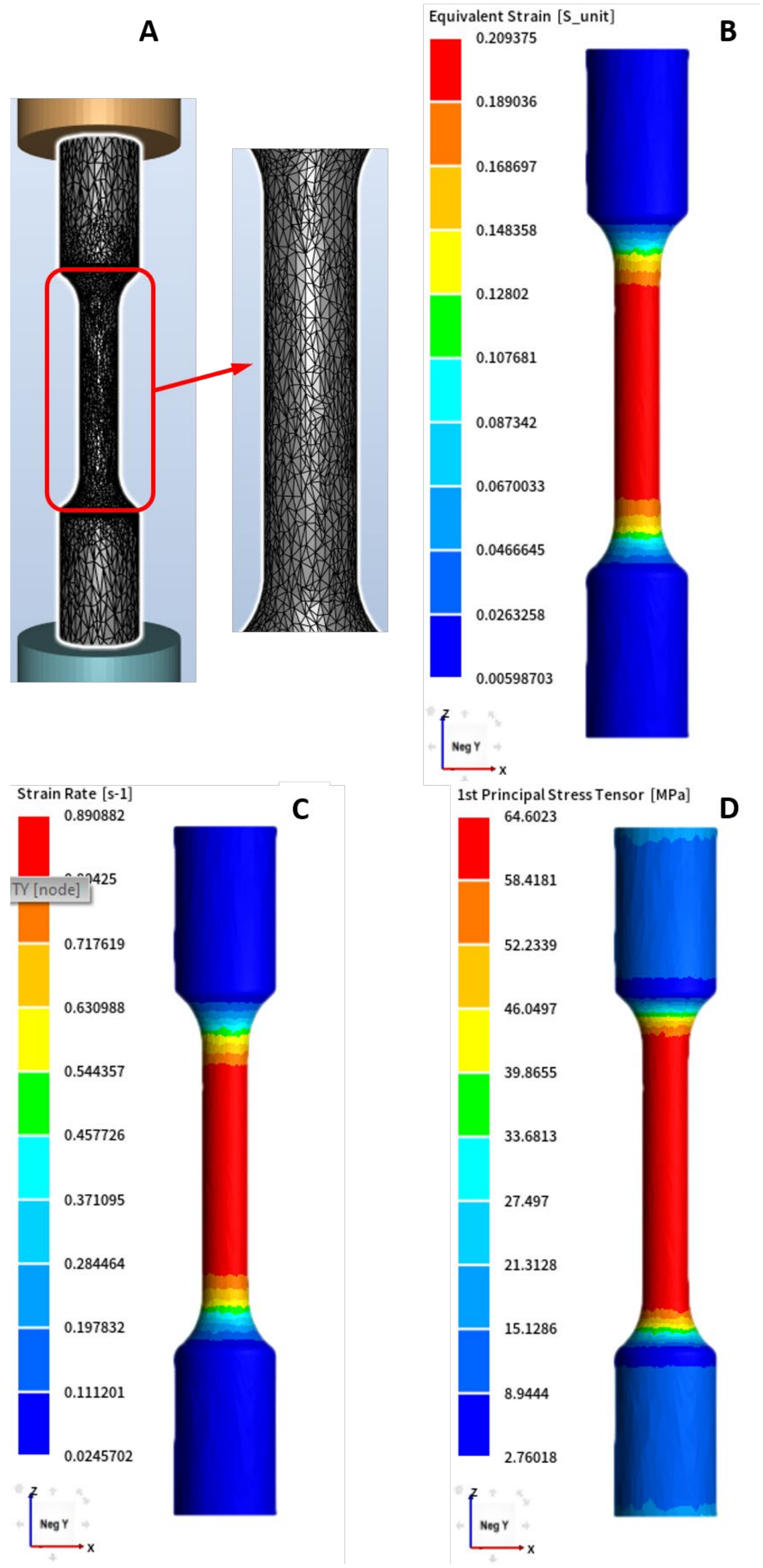

Fig. 2. Tensile test FE model and results for 1 s-1, 1000ºC case: (A) the rigid dies and deformable meshed sample; (B) Equivalent strain; (C) Strain Rate; (D) First Principal Stress

As it can be seen the results are evenly distributed in the middle section of the sample, which allows obtaining the values of the principal and effective stress inserting a sensor in the middle section without risk of errors.

The results obtained from the application of the mentioned methodology for obtaining C are gathered in Table 3.

Table 3. FEM models test conditions, and C values obtained for each of the cases for Super Cr 13 MSS.

Model #	Strain Rate	Tª [°C]	C
1	0.01	900	0.17
2	0.01	1000	0.21
3	0.01	1100	0.21
4	0.1	900	0.2
5	0.1	1000	0.22
6	0.1	1100	0.22
7	1	900	0.12
8	1	1000	0.31
9	1	1100	0.33
10	10	900	0.13
11	10	1000	0.47
12	10	1100	0.47

The important finding of this procedure is the fact that the critical damage value is a function of strain rate and temperature, not only depends on the accumulated strain. As it can be seen the increasing temperature and strain rate lead to higher C values.

Push Bench Elongator Process Analysis

The final step of this analysis is the application of the knowledge obtained from the laboratory tests to the study the Push Bench Elongator Process of Super Cr 13 seamless pipes. For that purpose, a 3D FE model of the process have been developed, following the indications of the industrial partner Tubos Reunidos s.l.u.

The main components of the Push Bench Elongator process are shown Fig. 3, considering the dimensions and relative disposition provided by the industrial partner, Tubos Reunidos s.l.u. It consists of an inner mandrel, and 10 stands of 3 rolls each. The rolls from one stand to the other are rotated 60º around tube axis, resulting in a staggered arrangement. The tube to be deformed is a hollow cylinder with the following initial dimensions:

- outer diameter = 206.2 mm,
- inner diameter = 154 mm,
- length = 4.27m.

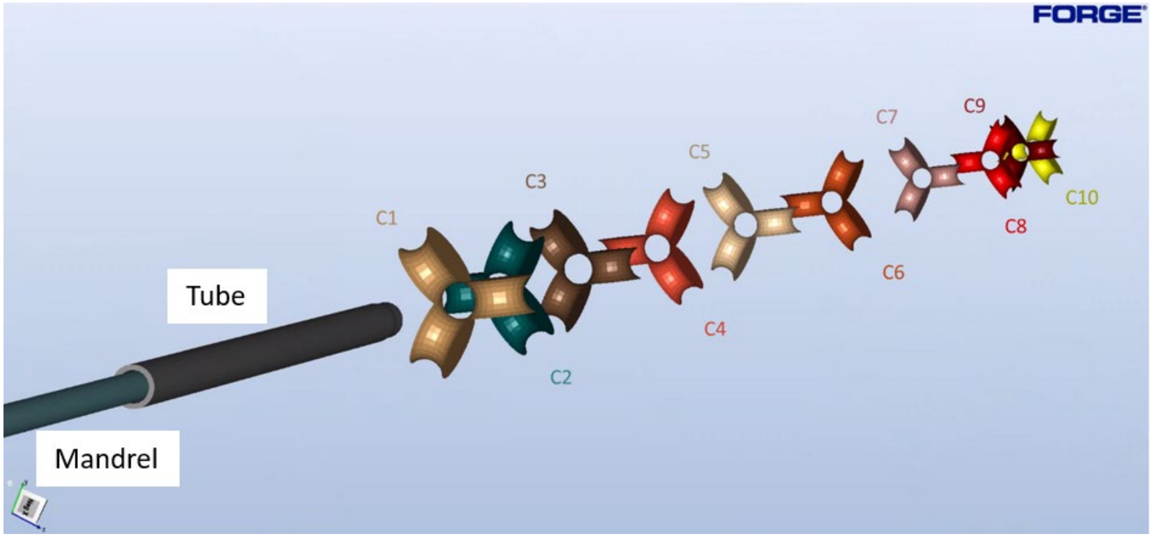

Fig. 3. Disposition of the elements of the Push Bench Elongation according to Tubos Reunidos.

The rolls have two important goals in this process. On the one hand, they are in charge of reducing progressively the outer diameter of the tube, and, consequently, the thickness of the wall. The reduction of tube diameter between stands is a key parameter of the process. This reduction is higher at the begging of the process and smaller towards the end. At the same time, they have to guarantee the circumferential profile of the tube at the end of the process. For this reason, the profile of the rolls plays a main role during the process. The rolls have an elliptical profile, since the groove has a larger diameter than that of the flanges. As a consequence, the theoretical positions of the centres of the tube cylinder and the rolls are not coincident; there is an eccentricity to favour the material flow. This eccentricity is bigger at the beginning of the process in the initial stands (coinciding with the diameter reduction), and is reduced progressively to be null in the last stands, resulting that the profile of the rolls in the last stands is circular. The geometry of the rolls and the separation between stands is confidential information.

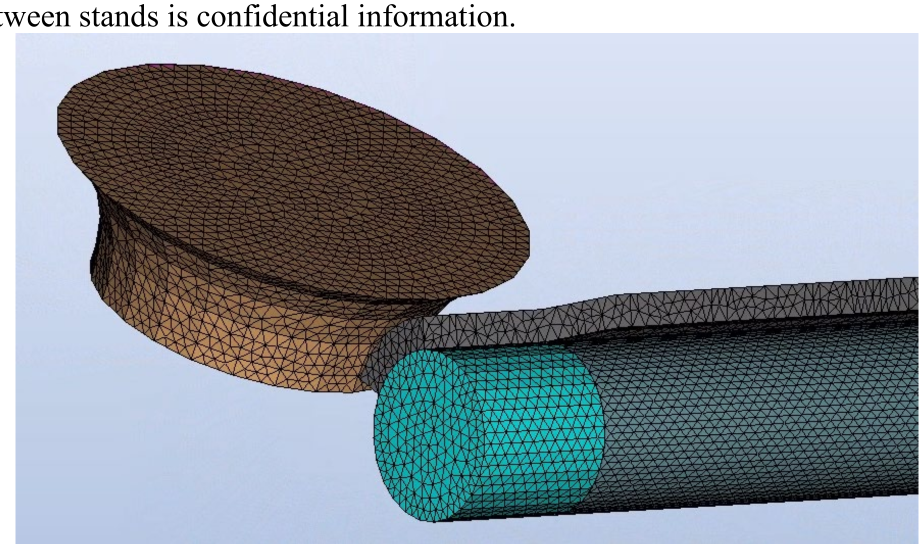

Fig. 4. Detail of the mesh of the FE model: roll, tube, mandrel and mandrel head.

Fig. 4 shows a detail of the meshed used for the FE model of the process, where the mandrel and its head, the tube and a roll of the first stand are plotted. The tube has been meshed with 3D tetrahedral P1+linear elements with a bubble node with a mesh size of 8 mm, with the aim of maintaining at least 3 elements in thickness of the tube, resulting in 115.538 elements. It is a deformable body according to Hansel-Spittel law and the coefficients gathered in Table 2. Rolls, and mandrel are rigid bodies with a mesh size of 12 mm, and 11 mm respectively.

As it can be seen in Fig. 4, the head of the mandrel is attached to the tube and has a linear velocity predefined of 5500 mm/min, during 40.000mm, to ensure the full tube to be rolled by the ten stands. The rolls have free rotation around their axis of symmetry.

Regarding the initial and boundary conditions, the initial temperatures are:

- tube: 1100ºC,
- mandrel: 400ºC,
- rolls and ambient: 50ºC

The heat transfer coefficients, h, considered are gathered in Table 3.

Table 4. Heat transfer coefficients of FE model

Components	h [$W/m^2 \cdot K$]
Roll-Tube	10.000
Mandrel-Tube	2.000
Ambient-Tube	10

For the friction between the rolls and the tube, and between the mandrel and the tube the Tresca friction law was selected, and friction coefficient of 0.3 for both contacts, according to experience.

The model above described has been used to assess the influence of two process parameters on the final tube geometry and risk of damage. The selected process parameters are: rolls ovality, and the friction coefficient. Two values of these parameters have been considered, resulting in 3 models, as described in Table 5:

Table 5. Description of the parameters used in the models

Model Name	**Coef. Friction**	**Ovality**
1. Base	0.3	1
2. ½ Friction	0.15	1
3. ½ Ovality	0.3	½

Thus, the comparison of the results of models 1 and 2, allows understanding the effect of friction. For this study, power consumption evolution and Latham and Cockcroft parameter are evaluated. The Latham and Cockcroft is an uncouple criteria, that is, it does affect material behavior due to damage. Its value is updated for every increment adding the damage increase between increments in each element of the mesh. On the other hand, the comparison of models 2 and 3 allows understanding the effect of ovality.

The ovality of the tube is related to that of the rolls, as it can be seen in Fig. 5, the ovality of models 1 and 3 are shown as well as the ovality of the rolls. The blue lines show the ovality of the original process, which lead to a final ovality on the tube that is relevant almost 50% higher than that of the rolls of the last stand. By contrast when the ovality in the las four stands is reduced to the half, the remaining ovality on the tube is reduced 65%.

The evolution of the wall thickness eccentricity is shown in Fig. 6 where the models 1 and 3 are compared, as well as the eccentricity of the rolls which are plotted in dashed lines. The blue lines correspond to the model 1, original, and there it can be seen that the wall thickness eccentricity increases greatly in after last stand, even though the eccentricity of the rolls remains constant. By contrast, in model 3 (red color) the eccentricity at the end increases slightly. Thus, a reduction of 50% of rolls ovality leads to a reduction of 64% in the final wall thickness eccentricity of the tube.

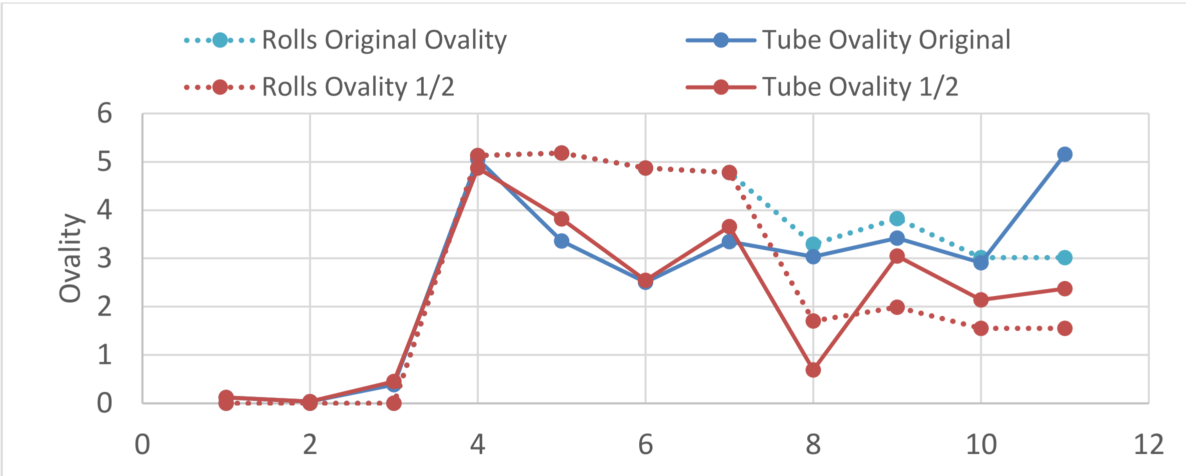

Fig. 5. Evolution of the ovality of the rolls and the tube during the forming process

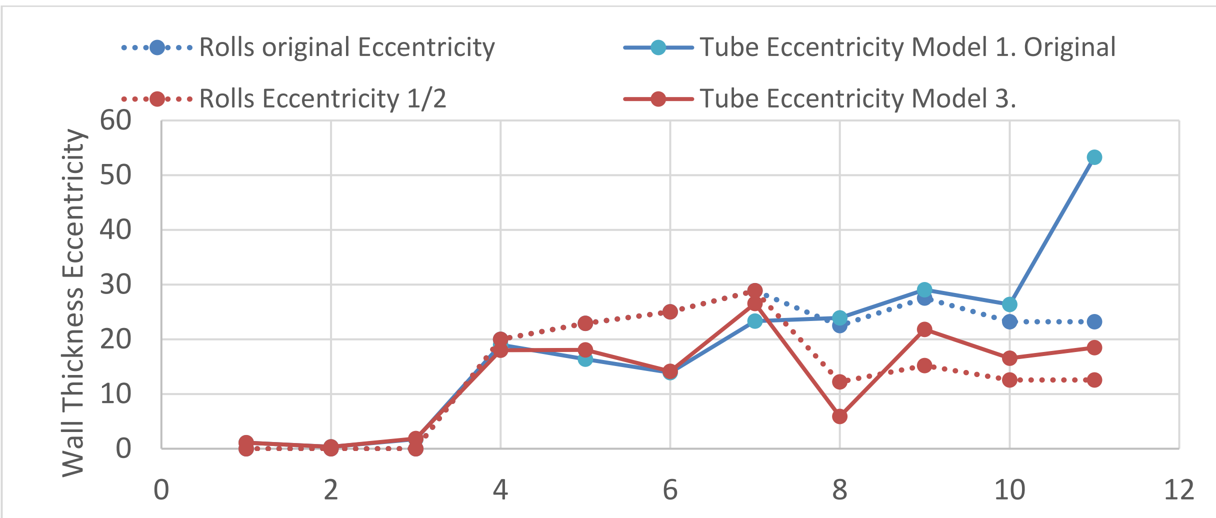

Fig. 6. Wall thickness evolution for the two models studied: model 1 (original) blue lines, model 3 red line

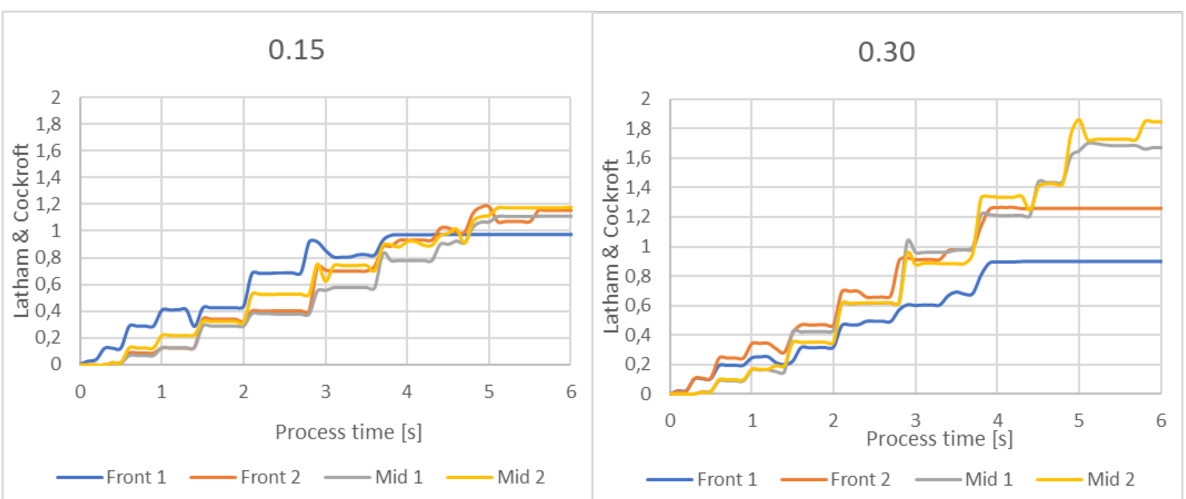

Fig. 7. Evolution of Latham & Cockcroft parameters during the rolling process for model 3, friction coefficient 0.15; and model 1, friction coefficient 0.30

Summary

In this paper the Push Bench Elongator has been analysed and the effect of two process parameters, namely, on the quality of the tube and probability of material damage have been assessed. For that purpose, first, an experimental hot tension test campaign has been developed to characterize the behavior of super Cr 13 MSS was developed. From the curves obtained from the tests the coefficients of Hansel Spittel equation were adjusted. Additionally, the tension tests have been simulated for determining the critical damage values of the Latham & Cockcroft damage criteria. Results show that these critical values vary depending on strain rate and temperature. Finally, a FE model of the process has been developed to study the effect of friction and ovalization on the tube. Results show a very high impact of friction in damage, and that the reduction of rolls ovalization in the last stands of the process have relevant positive influence.

References

[1] H. A. Derazkola, E.Garcia, A. Murillo-Marrodan 'The effect of temperature and strain rate on the mechanical properties and microstructure of super Cr13 martensitic stainless steel', Journal of material reasech and technology, 2023. https://doi.org/10.1016/j.jmrt.2023.04.012

[2] M. Reggio, F. McKenty, L. Gravel, J. Cortes, and G. Morales, 'Computational analysis of the process for manufacturing seamless tubes', Applied Thermal Engineering, 2002. https://doi.org/10.1016/S1359-4311(01)00093-X

[3] A. Yamane, K. Yamane, and H. Shitamoto, 'Development of Numerical Analysis on Seamless Tube and Pipe Process', Nippon steel and Sumitomo Technical Report 107, 2015.

[4] R. Langbauer, 'Investigation of the temperature distribution in seamless low-alloy steel pipes during the hot rolling process', Advances in Industrial and Manufacturing Engineering, 2021. https://doi.org/10.1016/j.aime.2021.100038

[5] J. Hu, S. Yang, Y. Huang, X. Wang, and J. Chen, 'A New Correction Theory and Verification on the Reducing Rate Distribution for Seamless Tube Stretch-Reducing Process', Crystals 2022. https://doi.org/10.3390/cryst12091296

[6] Z. Wei, 'A new analytical model to predict the profile and stress distribution of tube in three-roll continuous retained mandrel rolling', Journal of Materials Processig Technology 2022. https://doi.org/10.1016/j.jmatprotec.2022.117491

[7] Z. Pater and A. Gontarz, 'Critical Damage Values of R200 and 100Cr6 Steels Obtained by Hot Tensile Testing',Materials 2019. https://doi.org/10.3390/ma12071011

[8] F. Lastname, F. Lastname, and F. Lastname, 'Johnson Cook Material and Failure Model Parameters Estimation of AISI-1045 Medium Carbon Steel for Metal Forming Applications', Materials 2019.

[9] H. Zhang, M. Meng, X.Yang, G. Lei, J. Jia, G. Wu, X.Zhang, J. Yu. 'Hot tensile deformation behavior and a fracture damage model of the wrought Mg–Gd−Y–Zn–Zr alloy. Journal of Materials Research and Technology, 2022. https://doi.org/10.1016/j.jmrt.2022.02.104

[10] H. Vafaeenezhad, 'Using high temperature tensile testing data to analyze hot formability of Sn-5Sb alloy: instability and critical damage criteria'.