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Publisher's version / Version de l'éditeur:
https://doi.org/10.4271/2010-01-0224
SP-2294: Advances In Light Weight Materials – Aluminum, Casting Materials, and Magnesium Technologies, SP-2294, pp. 1-16, 2010-04-13

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10M-0108

Numerical studies on the production of variable thickness aluminium tubes for transportation purposes

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ABSTRACT

Nowadays application of light alloys like aluminium in automobile industry has found a striking role. Higher strength over weight ratio which causes lower fuel consumption seems to be the first reason. Also some other reasons like ease of manufacturing, protection against corrosion and ease of recycling are other motivations for car designers to use various aluminium alloys as much as possible. Due to lack of variable thickness tubes, they have not found a lot of applications in the car component design. This paper aims to introduce these types of tubes to automotive industry. Also these tubes are one of the essential elements in the complementary processes like tube hydroforming and cause ease of production and decreasing risk of scrap in manufacturing cycles. Tube drawing is one of the mostly used methods for reducing thickness and/or diameter of tubes which, can be classified in four categories like sinking (without mandrel), float mandrel, fixed mandrel and ultrasonically moving mandrel. This paper presents numerical studies that have been done on the drawing tubes with variable thickness. The influence of process variables on material thinning and formability in 63.5mm outer diameter, 2.62 mm wall thickness AA6063 aluminium alloy tube, were investigated and optimised. Validation of the numerical simulation on the different parameters setting will be performed by comparing the final shape and deformation, measured from the tested part. Acceptable agreement between numerical and experimental results was observed.

INTRODUCTION

TUBE DRAWING

The use of aluminium and its alloys in vehicles is not new to the experts in this area. Since 1991, the use of aluminium alloys in North American cars increased 113% from 1889 to 4041 million lbs (pounds). In 1999, the total average weight of aluminium in a North American vehicle was around 230 lbs (GM, 271 lbs; Ford, 222 lbs; and DC, 193 lbs). Fuel economy improvements of around 6%-8% can be realized for every 10% weight reduction in a vehicle. Every pound of aluminium that replaces 2 lbs of steel can lead to a net 20 lbs of CO_2 equivalents over the lifetime of a vehicle [1]. Weight savings up to 40%-50% are achievable when mild steel parts are replaced by aluminium alloys as density ratio is 3:1. Automobile components made of aluminium are usually: a) frames, b) bumper beams, c) side impact beams, d) engine cradles, e) chassis parts, f) suspension elements, g) body, and h) engine blocks. Almost 80% of aluminium content is due to the use of cast aluminium parts for engines, transmissions, and wheels. However, aluminium body parts hold only 8%-10% of aluminium use in North American cars. On the other hand, aluminium is 3-4 times more expensive than steel, and almost 50%-60% of total part price is material related. Its formability at room temperature is much lower than that of steel (two-thirds of drawing quality steel). It is more susceptible to forming defects such as wrinkling and springback when compared to mild steel. Even though there is a huge potential for further fuel savings by using aluminium for body, chassis, and other structural parts, the justification of aluminium structural parts over steel is very difficult and questionable with conventional production processes like forging and stamping because of the cost and formability constraints [2,3]. Each improvement in fabrication methods of aluminium parts is a step toward for more utilization of aluminium in cars. In this paper, a new modification to production of aluminium tubes is presented. With this modification which implemented to tube drawing process, the mass production of variable thickness aluminium tubes got possible. The numerical studies is performed with Ls-Dyna software and validated with the experiments performed by prototype machine which manufactured by this group and depicted thoroughly in [4].

The method presented in this paper is not the sole method for producing variable thickness tubes, but it is among the fastest and most flexible methods. The other methods like radial forging or indentation forging are not as flexible as this method in having thickness variation along length of tube. For instance in indentation forging just some helical slots in thickness of tube can be created [5,6] or in the radial forging method, the thickness variation should be in a way that mandrel can pass through the tube [7].

In tube drawing process, tube is inserted in the die and then gripped by a suitable device which can pull it forward on a mechanical or hydraulic bench which causes reduction in the outer diameter and wall thickness of part. Depending on the process parameters like thickness reduction, material property, lubrication and design of die and mandrel, maybe it is necessary or not to perform the tube drawing in one or two steps. Common methods for this process are i) sinking (without mandrel); ii) fixed plug, in which the mandrel is positioned and fixed with a long rod. iii) floating mandrel in which mandrel is no longer connected to anywhere iv) ultrasonically vibrating mandrel in which the ultrasonic vibration of the mandrel gives some benefits like reduction in required force.

The tube drawing and similar processes like wire drawing have been subject of various papers since 1962. During this period various aspects of this process evaluated analytically (energy, slab and upper bound methods) and numerically for various materials [8-18].

In this paper, the numerical study of tube drawing with variable thickness (Fig.1) is presented and compared with experiments. Results were used to optimise the performance of prototype machine designed at the Aluminium Research Centre at Laval University.

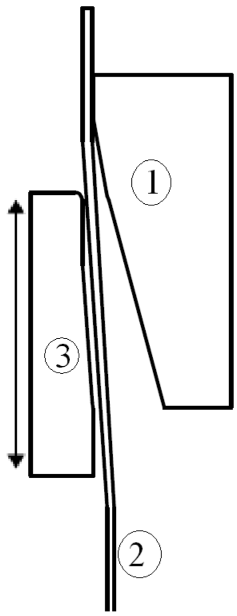

Fig. 1) The schematic concept for production of variable thickness tube. 1) Die 2) Tube 3) Mandrel (The movement direction of mandrel is in the axial direction of tube).

NUMERICAL MODELLING

The axisymmetric nature of geometry and loading, leads this process to be modelled as axisymmetric elements in Ls-Dyna software. At the same time, a 3D model was tested and it was produced that the results are almost the same results as those of the axisymmetric one.

Geometries of die, mandrel and tube were designed in SolidWorksTM software and imported in HypermeshTM software for meshing. The meshed parts were then inserted in Ls-Prepost for defining model details like boundary conditions, mandrel and tube displacement curves, and material properties, etc..

MATERIAL PROPERTIES

AA 6063-O was the material used in both numerical and experimental studies. Piecewise linear plasticity was chosen as material model. Fig. 2 presents the stress-strain curve of this material obtained from tension tests and extrapolated up to higher strains based on the power law $(\sigma = A\varepsilon^{B} + C)$ [19].

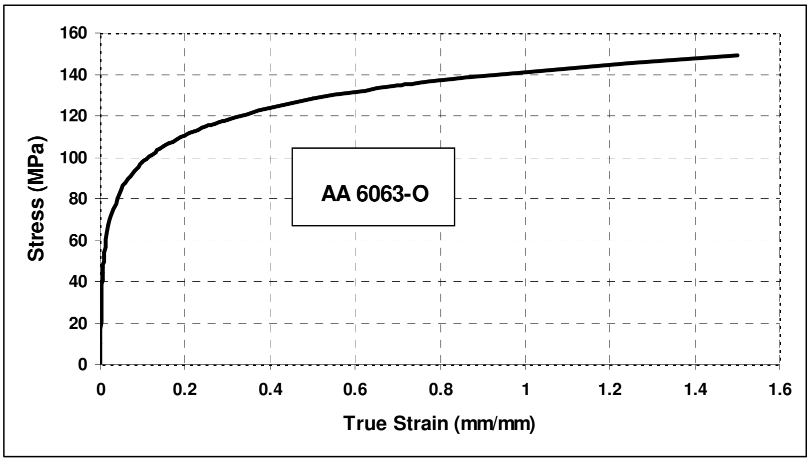

Fig.2 Stress-Strain curve for tube material (AA 6063-O)

BOUNDARY CONDITIONS

As in the real process the mandrel was left constrain free in the axial direction and just constrained in the radial direction. Also for variational movement of mandrel in the axial direction, a curve is defined then it was attached to prescribed motion of mandrel. The success of the process in experiments depends strongly on an appropriate design of this curve. In other words, the distribution of thickness along the tube axial direction, minimum thickness and its distribution along the tube axis and rate of deformation are implemented by this curve. For the die, it was constrained in all directions as a rigid part and for the tube motion, a displacement is prescribed at one end of the tube.

EXPERIMENTS

The tube drawing machine illustrated in Fig.3 was designed and built at Laval University and will be used for all experimental tests. The parameters extracted from experiments and compared with numerical models are reaction forces on the die, mandrel, and required force for pulling the tube.

The hydraulic drawing machine has two axes, a tube pulling axis with a stroke of 2.1m and a capacity of 377kN and a mandrel axis of 1.5m and 167kN. Both axes are servo-controlled and their position, speed and force are monitored. Typically, the tube pulling axis is controlled for constant speed while the mandrel is controlled in position to achieve a given thickness. More details on this machine are available in [4].

Fig.3) Experimental rig for tests: 1) cylinder for pulling the tube, 2) location of installation of die, 3) cylinder for movement of mandrel.

Fig.4) The tube produced using tube drawing machine of Laval University.

RESULTS AND DISCUSSION

VALIDATION OF NUMERICAL MODEL

In the first step of numerical studies, it was necessary to have a validated and calibrated model in which the parameters of variable thickness tube drawing process were studied and tried to be chosen as optimum as possible.

The tube which used in experiments has O.D=63.5mm and thickness of 2.62mm. The material was AA 6063-O and lubricant was CAL 70-2. The mandrel and tube end motion curves which used in the experiments are presented in the Fig.s 5-6.

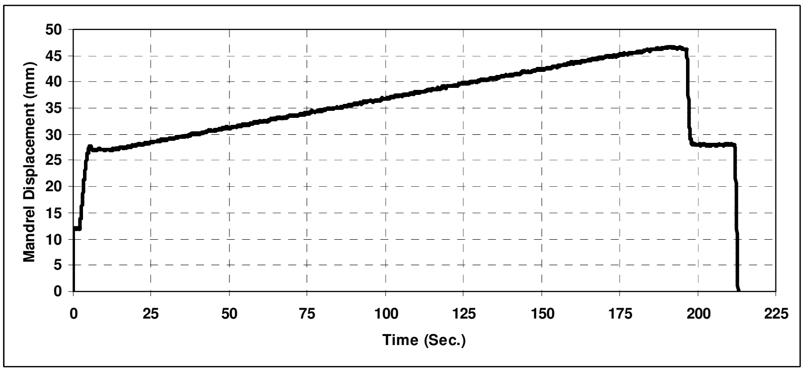

Fig. 5) Mandrel displacement during forming process.

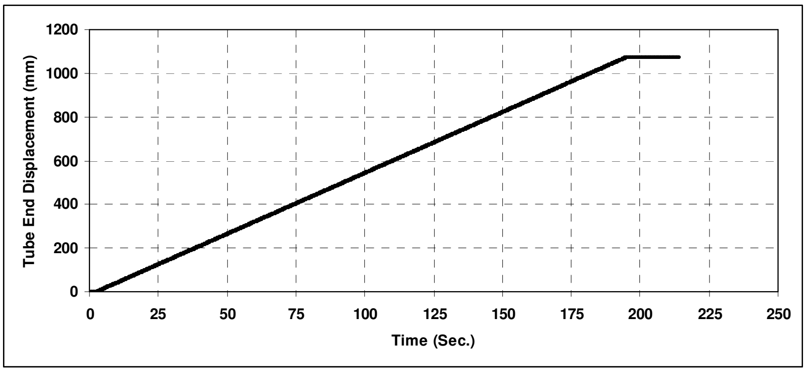

Fig. 6) The curve used for the motion of tube.

Fig.s 7 and 8 present reaction force on the mandrel from experiments and FE model (These two curves were not plotted in the same graph because the real process was performed during 215 seconds (tube deformation happened between 10th and 170th seconds) but in the FE model the time was scaled to 1 second). In the experimental curves, at the beginning of the drawing process, there is a local peak in the reaction forces which seems to be the effect of initial contact of mandrel and load cell. There is also a steady state positive force in the experimental force before negative reaction forces which seems to be required force for positioning mandrel up to 70th second and the deformation process forces starts after this time with trend and slope similar to result of FE model and as it was expected there is not such a positive forces in the numerical results. As process continues the force increases up to reaching the minimum desired thickness and after this point a steady state in the load curve is expected if the process continues to produce same thickness. The difference between the reaction forces predicted experimentally and numerically is 519 N (9.8%). The difference can be because of not complete lubrication of forming zone or misalignment of mandrel road during the experiments and also some uncontrollable errors in the load measurement.

Similarly Fig.9 and 10 present the comparison between the reaction force on the die from experimental result and FE model. Unlike to the mandrel force there is not any positive reaction force in the die force curve. When the process starts there is a jump in the 5 initial seconds of process which seems to be due to initial positioning of tube. After that there is a steady state in the forces which like mandrel exactly finishes in the 70th second and after this time the force because of deformation starts and reaches to maximum of -35KN and after that force has steady state. The difference between predicted reaction force for the die from experiment and FE was about 4.14% (1.73 KN).

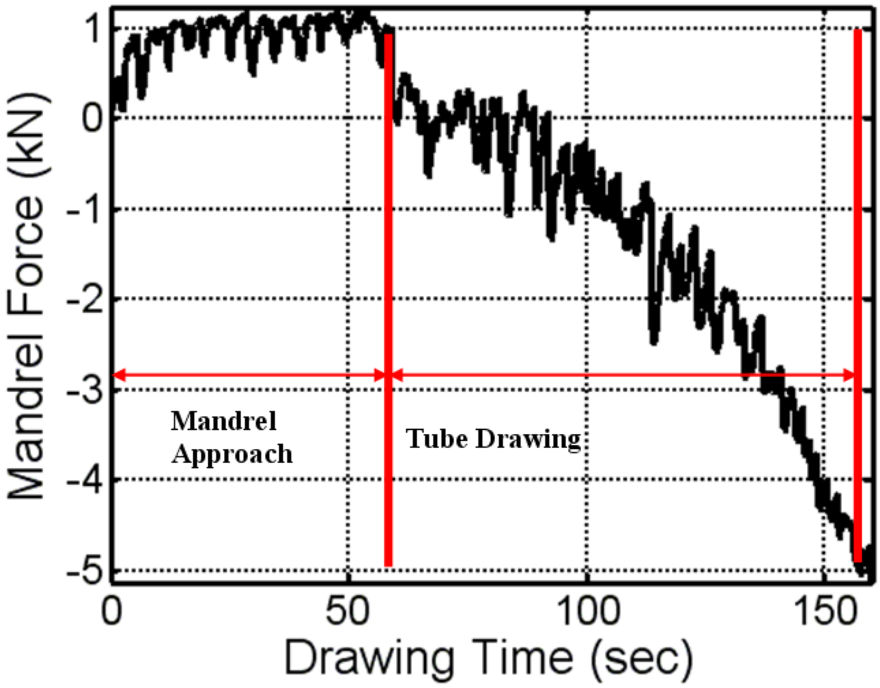

Fig. 7) Reaction force on the mandrel (Experimental)

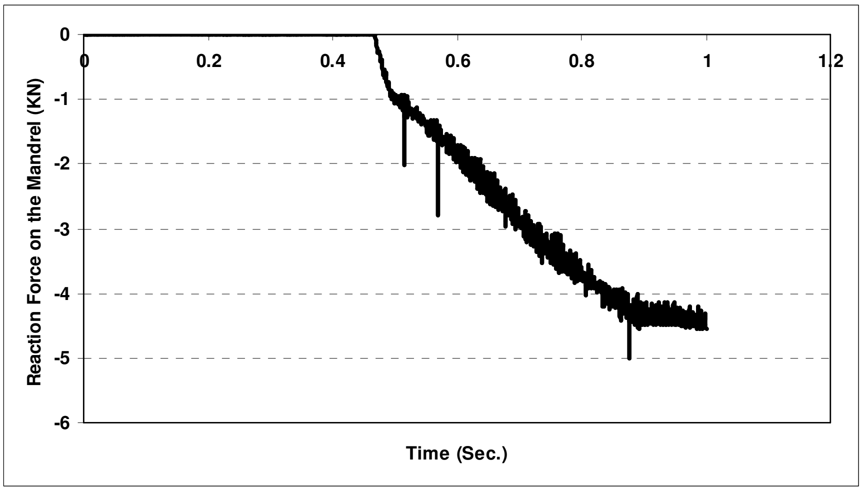

Fig.8) Reaction force on the mandrel (from FE)

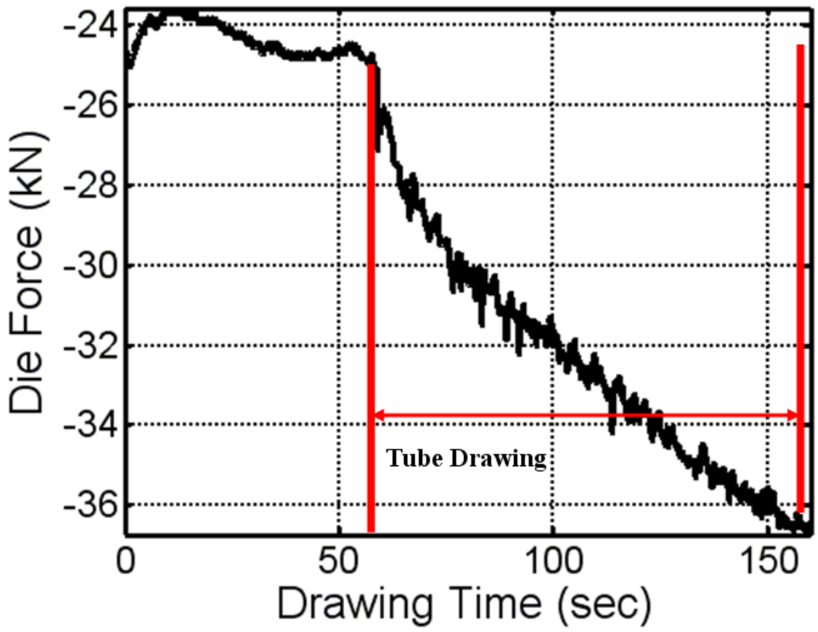

Fig. 9) Reaction force on the die (Experimental)

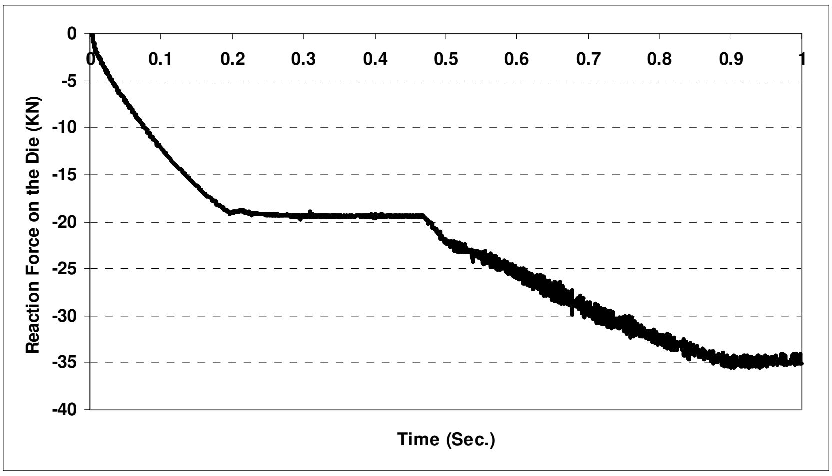

Fig.10) Reaction force on the die (From FE)

In Fig.s 11 and 12 the required force for tube drawing were presented. The tube drawing force is sum of reaction forces on the die and mandrel. Therefore the trend and peaks are exactly the same. The experimental force is 42KN while the predicted force from FE model is 40KN which seems to be an acceptable error for a FE model.

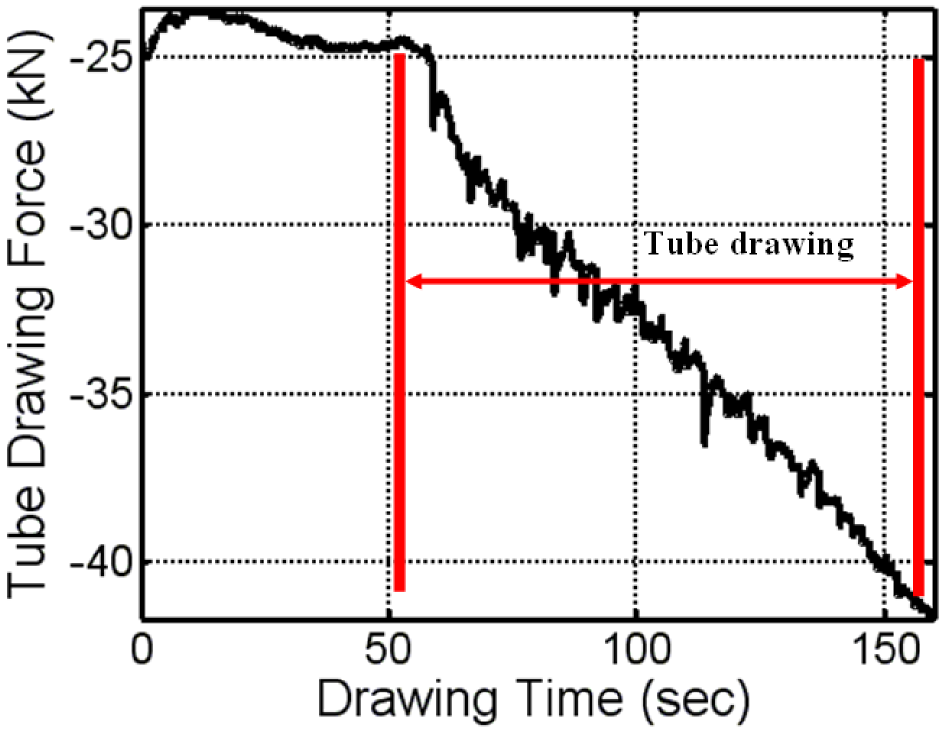

Fig. 11) Tube drawing force (Experimental)

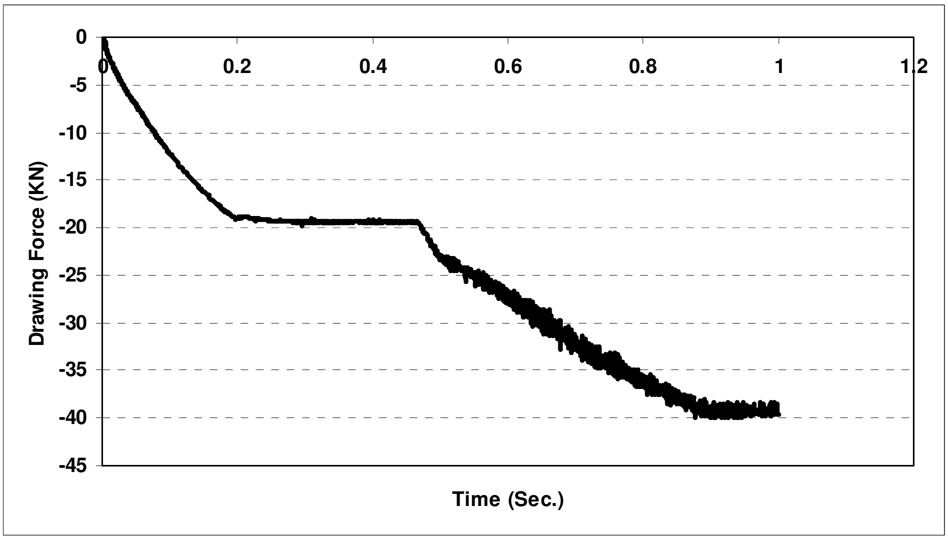

Fig. 12) Required force for pulling the tube through the die and mandrel (From FE)

State of strain with respect to FLD curves

In Fig. 13 state of major strain (axial strain) with respect to minor strain (hoop strain) was plotted. As it is seen on this figure, there is an acceptable distance between the FLD curve [20] and state of strain for the element with maximum thickness reduction. Therefore no failure is expected during the drawing.

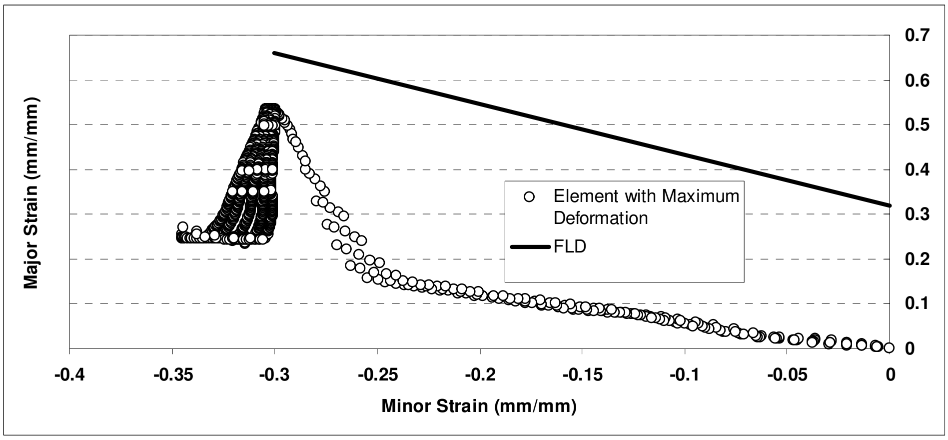

Fig.13) State of major and minor strain with respect to FLD curve [19]

NUMERICAL RESULTS

The process of variable thickness tube drawing is a new modification in production of tubes. Therefore it seems necessary to evaluate the effect of various process parameters on the final part and optimum performance of the process.

Effect of friction

In almost all forming processes, the effects of friction are well known and can be reduced with the use of high pressure or forming lubricants. This will reduce tooling wear, decrease drawing forces, avoid slip-stick effects on the mandrel and lower residual stresses after tube drawing. In addition with variable thickness tube drawing, lower friction can mean the use of only one reduction step instead of two. It is expected that a friction coefficient increasing from 0.05 to 0.15 has a detrimental effect especially on the drawing forces and on the risk of tube cracking. We observed in numerical simulations local necking in the drawn region of tube with friction coefficient above 0.08. Therefore the limitations in the drawability of tubes are restricted by the axial load (stress) endured by the tube in the drawn zones. A similar phenomenon was confirmed for the aluminium tube drawing at constant thickness [21]. Fig. 14 shows necked region in the tubes with friction coefficient of 0.1.

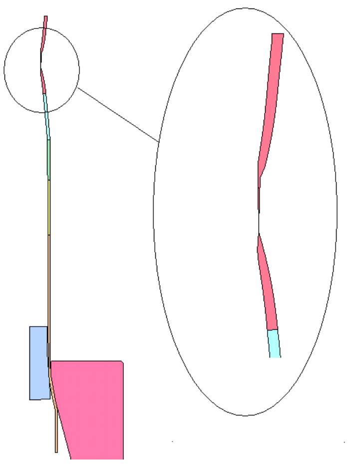

Fig. 14) Necked region in the tube with friction coefficient of 0.1.

As it is mentioned, the success or failure of this process strongly depends on the lubrication condition or in other words, for each level of friction coefficient there is a specific achievable amount of thickness reduction.

The first three simulations with friction coefficient of 0.15, 0.10 and 0.08 led to strain localization in a zone far away from the drawn tube. Table 1 presents achievable thickness reduction in each level of friction. As it is clear for the change of friction coefficient from 0.04 to 0.10 the amount of thickness reduction reduced 0.67 mm or 25.6%. The case is more robust for the friction coefficient of 0.15 which just 0.07mm or 2.67% reduction in thickness is achievable.

State of stresses in the tubes of variable thickness

Quantitative measurements of residual stress in the concave or convex surfaces of tubes are not easy to do. Therefore, one of the best applications of developed FE model is to predict the residual stresses state in the drawn tube.

Fig. 15 shows position of four points in the tube at which the stress state is analysed. Fig. 16 presents history of axial stress at those points. Point 1 had experienced less strain in thickness (maximum thickness) and points 3 and 4 are points with maximum strain (number 4 is located in the edge of tube). As shown in all 4 graphs, there is a local peak in stress which presents the time at which those points cross the die and mandrel. After this point, a steady state of stress is observed. At pseudo-time equals to one, there is the unloading zone, and it characterizes the amount of residual stress in the axial direction. There is about 26.8 MPa difference in the amount of residual stress between the points with minimum and maximum amount of strain. On the other hand, for the point located exactly in the end of tube, the amount of residual stress is almost zero which seems to be due to edge effects in this region

Table1: Minimum thickness reached without failure

Friction Coefficient	Minimum Thickness(mm)
0.04	1.72
0.06	1.79
0.07	1.89
0.08	2.06
0.10	2.39
0.15	2.55

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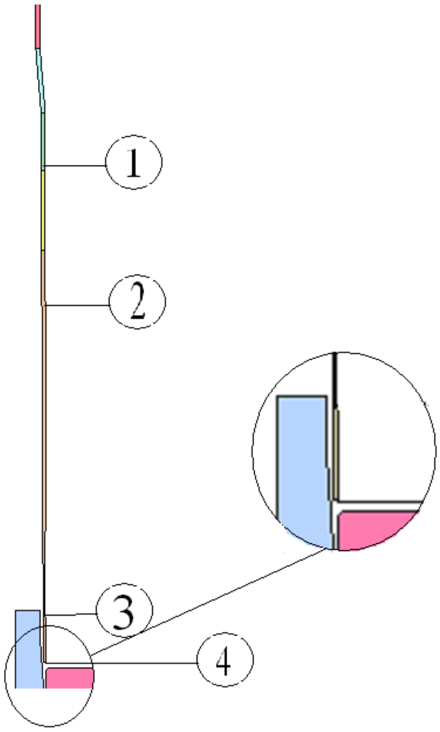

Fig. 15) Positions of 4 points where history stress and residual stresses were evaluated.

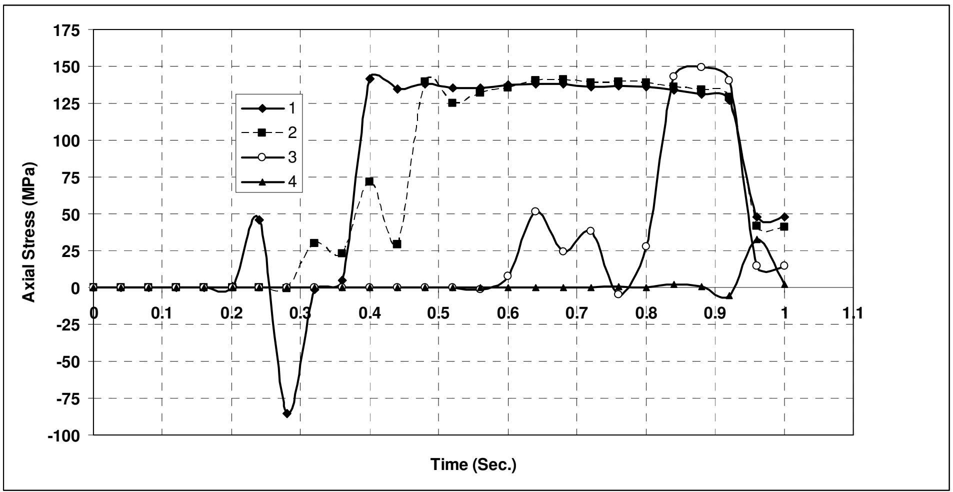

Fig. 16) Axial stress history of four different elements in outer surface of tube (Point No.1 has less deformation and points 3 and 4 have maximum amount of deformation and point 4 is located in the edge of tube)

For the inner surface of tube, the same difference for residual stress is observed. But the stress difference in the regions with less strain are considerably higher i.e. 123 MPa, and it is a compressive residual stress zone. Depending on the loading direction and type of tube the compressive residual stress can be useful in increasing fatigue life time of part.

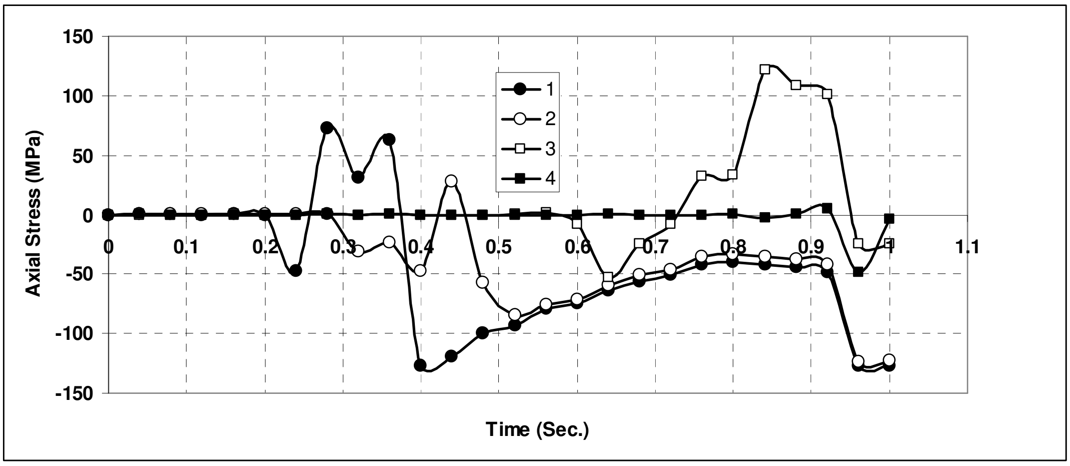

Fig. 17) Axial stress history of four different elements in inner surface of tube (Point No.1 has less deformation and points 3 and 4 have maximum amount of deformation and point 4 is located in the edge of tube)

In figure 18, history of hoop stress for the same four points previously identified, is presented. There are some local peaks with negative (compressive) hoop stress and positive stress in the steady state for points 1 and 2. Also in unloaded time, the amount of stress (residual stress) is positive with the amount of 50MPa in the regions with less deformation (points 2 and 3) and 25MPa in the regions with more deformation (point 3). There is a jump in the amount of residual stress in the edge of tube i.e. 85MPa which is due to edge effects. Therefore if the outer surface of the tube is going to undergo dynamical loading in hoop direction, the stress relive operation seems to be necessary.

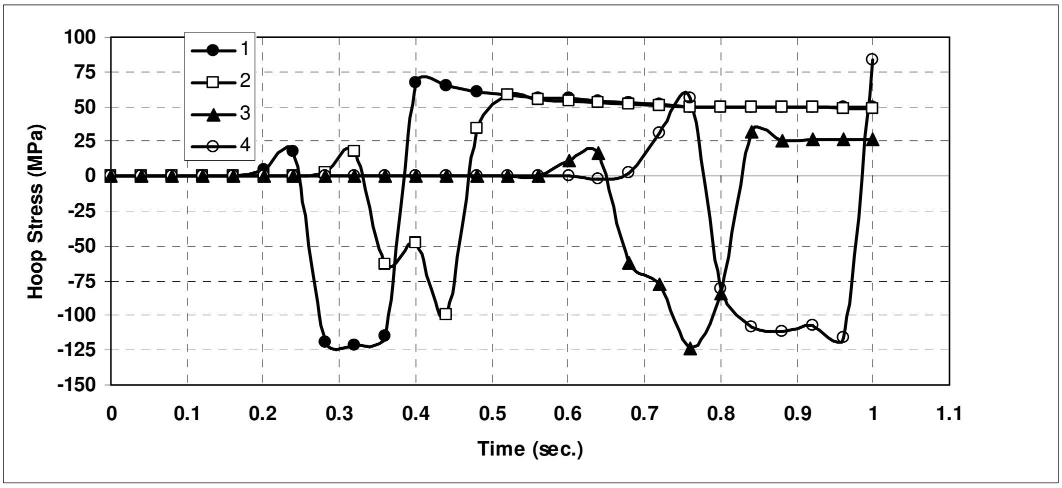

Fig. 18) Hoop stress history of four different elements in outer surface of tube (Point No.1 has less deformation and points 3 and 4 have maximum amount of deformation and point 4 is located in the edge of tube)

In the Fig. 19, the state of stress in hoop direction in four points of the inner wall of the tube is presented. The residual stress in the regions with less deformation is higher (105MPa) and in the regions with more deformation is less (84.2 MPa) but both of them are compressive which can enhance the fatigue life time in dynamics loading in the hoop direction.

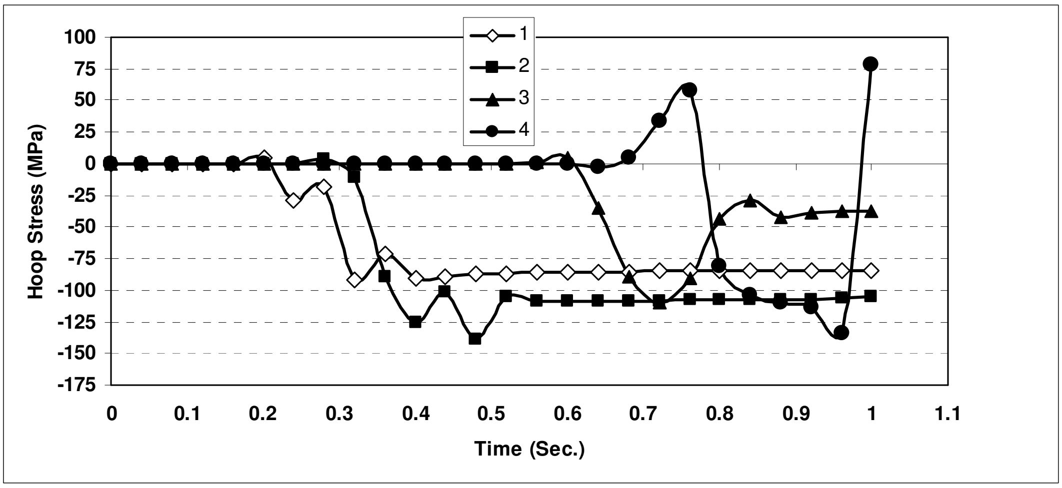

Fig. 19) Hoop stress history of four different elements in inner surface of tube (Point No.1 has less deformation and points 3 and 4 have maximum amount of deformation and point 4 is located in the edge of tube)

SUMMARY/CONCLUSIONS

In this paper the new method for production of variable thickness tubes was introduced and developed in a FE model. Also some experiments for validation of numerical model were performed and based on the validated model, the following conclusions can be written:

The concept of moving mandrel while drawing tube worked well and is an easy to implement and flexible method for production of tubes with variation of thickness in the axial direction.

The lubrication of contact interface between tube, die and mandrel is very important and for some levels of friction it will cause complete failure of tube before completion of the drawing.

The state of residual stresses in the outer surface of tubes in the axial and hoop directions (most susceptible direction of loading for thin wall tubes) are tensile which can cause reduction of fatigue life time of tubes in dynamics loading.

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ACKNOWLEDGMENTS

The authors thank the National Sciences and Engineering Research Council of Canada, Alfiniti, Aluminerie Alouette, C.R.O.I and Cycles Devinci for the financial support of this research. A part of the research presented in this paper was financed by the Fonds québécois de la recherche sur la nature et les technologies by the intermediary of the Aluminium Research Centre – REGAL. Also suggestions and helps of Mr. Jean-Francois Béland, researcher at the Aluminium Technology Centre were highly appreciated.