LS-DYNA® used to analyze the drawing of precision tubes

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Summary:

Long precision tubes are commonly made using the floating plug tube drawing process. The process has been analyzed using various methods e.g. upper bound method and FEM [1-10]. The die land and the plug land are usually cylindrical and form a cylindrical bearing channel between the die land and the plug land. The influence from the length of the bearing channel on the drawing force has only been dealt with in very few papers. In [2] it is recommended to use the shortest possible bearing channel in order to reduce the drawing force. A short bearing channel is also recommended in [6] both in order to reduce the drawing force, but also in order to increase the stability of the drawing process. The authors have not found any papers dealing with which influence the shape of the bearing channel has. The paper describes an analysis of tube drawing with a floating plug carried out using LS-DYNA®. The analysis shows that the drawing force, with conventional tooling, is heavily influenced both by the length and the shape of the bearing channel. The analysis has given inspiration to a new plug design, where the cylindrical plug land is replaced with a circular profiled plug land. Simulations of tube drawing with the new plug design show that the drawing force can be decreased and that the drawing force is nearly independent of the length of the die land and of small variations in the die land angle.
With a conventional plug it is necessary at start up to make a dent in the tube behind the plug in order to force the plug into the right position in relation to the die. Without a dent the plug will be pushed ahead of the die and no reduction of the tube wall thickness will take place between the plug land and the die land. The dent is commonly made manually with a hammer and making the dent is difficult. If the dent is not made big enough the plug may pass the dent without being brought in the right position in relation to the die and if the dent is made too large this may lead to tube fracture. To ease the threading process at start up it is suggested to make the plug with a conical front end. By doing so the plug becomes self-catching; that is the frictional forces between the conical front end and the inside tube wall will set the plug in the right position in relation to the die during start up. Simulations show that the “self-catching plug” principle works.

Keywords:

FEM, LS-DYNA, metal forming, tube drawing, floating plug, plug design

1 Introduction

Figure 1 shows a sketch of conventional tube drawing with a floating plug. The plug is kept in the equilibrium position by the balance of the frictional and the normal forces acting on the plug. The authors have found very little information in the literature regarding the influence from the length of the plug land Lp and the length of die land Ld. In [2, 6] is recommended to make the length of the bearing channel (the cylindrical section between the plug land and the die land, see Figure 1) as short as possible in order to reduce the drawing force. If the length of the bearing channel is too long, the frictional forces on the plug will pull it too far forward, pinching off or fracturing the tube wall. However the length can not be made arbitrarily small; if the length of the bearing channel is too small plug chatter may occur.

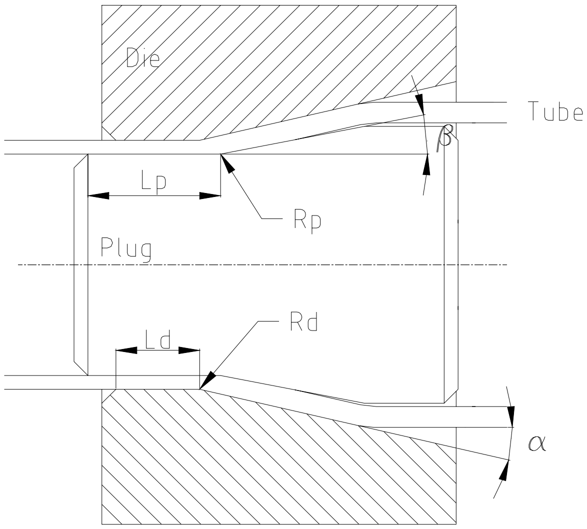

Figure 1: Sketch of conventional tube drawing with a floating plug

One of the purposes with the research carried out was to analyses the influence from the length and the shape of the bearing channel. The simulations were carried out as 2D rotational symmetric using LS-DYNA®. It was decided to carry out the simulations using implicit time integration. It is the experience of the authors that when simulating rotational symmetric metal forming process nearly identical results can be obtained with explicit and implicit time integration and that the CPU time is significantly smaller with implicit time integration, provided that the simulation runs through without convergence problems (unfortunately it is very difficult to foresee if convergence problems will be encountered).

2 Tube drawing with a floating plug of a tube from ø32*1.2 mm to ø30*1 mm

The tube drawing process which has been analysed is the drawing of an aluminium tube from ø32*1.2 mm to ø30*1 mm, and according to the company making the tubes, the tools used have the following dimension (see Figure 1):

semi angle of the die α : 13^0
length of the die land Ld: 3 mm
radius Rd: max 0.03 mm
semi angle of the plug β: 11^0
length of the plug land Lp: 8 mm
radius Rp: max 0.03 mm

2.1 FEM model

Figure 2 shows the FEM model. The tube was made up of two parts, a tube inlet, which was only used to “start” the tube drawing, and the tube which was modelled 50 mm long and meshed with 10 elements through the thickness and 500 elements in vertical direction. The elements used were 4 node elements (shell type 15) with 4 integration points. The tube was modelled as isotropic linear hardening (MAT_003) with the following parameters: E: 70,000 MPa, PR: 0.3, SIGY: 100 MPa, ETAN: 50 MPa. The tools were modelled as rigid. The die and the plug had all rotational degrees of freedom constrained. The lower nodes of the tube inlet were constrained not to move in vertical direction and the die was prescribed to move 50 mm in vertical direction with constant velocity. The total simulation time was 100 sec and was carried out in approximately 5000 time steps (with automatically adjusted time step size with max time step 0.02 sec).

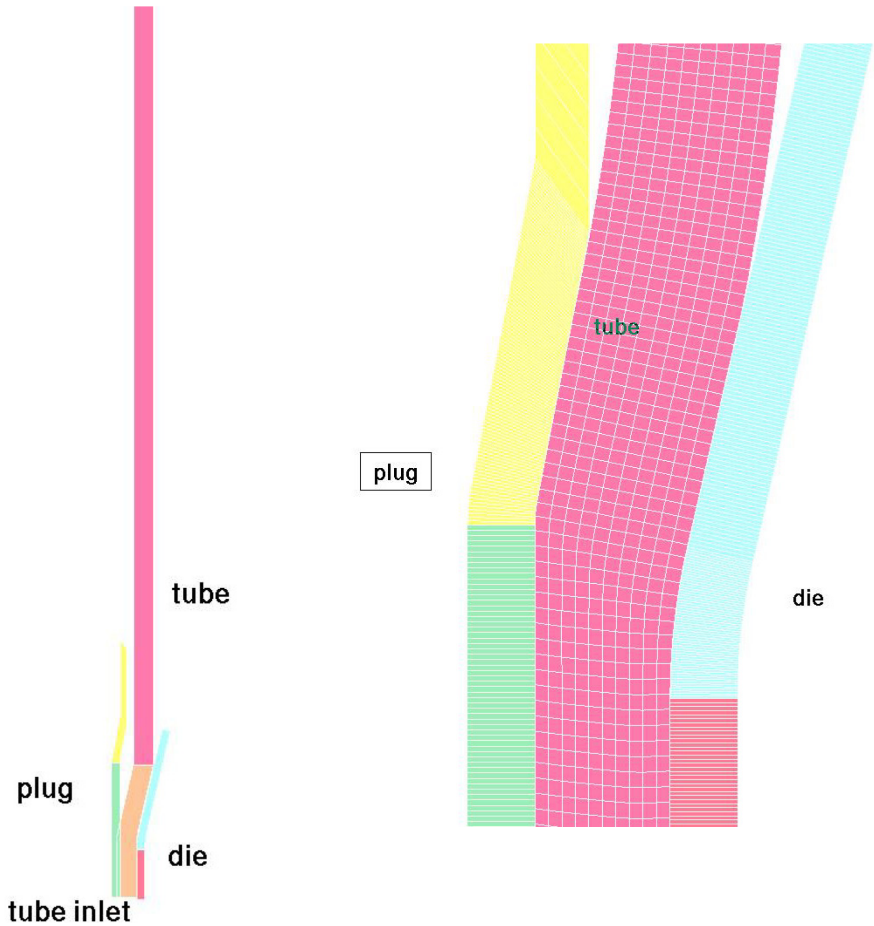

Figure 2: The 2D FEM model of the tube drawing carried out with the conventional design of die and plug. To the right is shown a close up of the deformation zone

The radii Rd and Rp (see Figure 1) on the real tools are very small. Seen from a FEM point of view it is not very nice to have material flowing past a sharp corner. The die in FEM model was thus made with a radius Rd = 5 mm and the plug with a radius Rp = 1 mm. If the FEM model of the die had been made with a sharp corner this would most likely had given rise to contact problems and to severe mesh distortion.

2.2 Contact parameters.

When simulating extrusion processes it is very important but also difficult to capture the contact forces in the bearing channel correctly. Both simulations and experiments show that very minor changes in the geometry of the bearing channel have a significant influence in the direct extrusion process [11], in the backward can extrusion process [12] and in the ironing process [13].
The contact was modelled using *CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE and assuming Coulomb friction in all contact interfaces.
To the experience of the authors the following parameters (besides from the values of the friction coefficient in the plug-tube interface μ_{plug} and in the die-tube interface μ_{die}) can have a significant influence on the contact forces in the bearing channel and on the simulations time:

dctol and dnorm on the *CONTROL_IMPLICIT cards
sfact and cof on the *CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE cards

The tube drawing was carried out with the values of dctol, dnorm, sfact and cof in both the tube-plug and tube-die interface as listed in Table 1. The CPU time to carry out the simulations are also listed. All the simulations listed in Table 1 were carried out with $\mu_{die} = \mu_{plug} = 0.05$.

	COF	SFACT	DNORM	TIMESTEPS	DCTOL	CPU-TIME (min)
Static	1	0.5	2	5000	0.001	22
Static	1	0.5	1		0.001	Failed due to convergence problem
Static	1	0.5	1	5000	0.01	142
Static	1	0.5	1	5000	0.1	82
Static	1	0.05	2	5000	0.001	107
Static	0	0.5	2		0.001	Failed (the plug stuck to the tube)
Dynamic	1	0.5	2	5000	0.001	104

Table 1: Simulations were carried out with values of COF, SFACT, DNORM and DCTOL as listed in the table. ($\mu_{die} = \mu_{plug} = 0.05$)

Figure 3 shows the vertical force on the conical part of the die and on the die land for the simulations listed in Table 1.

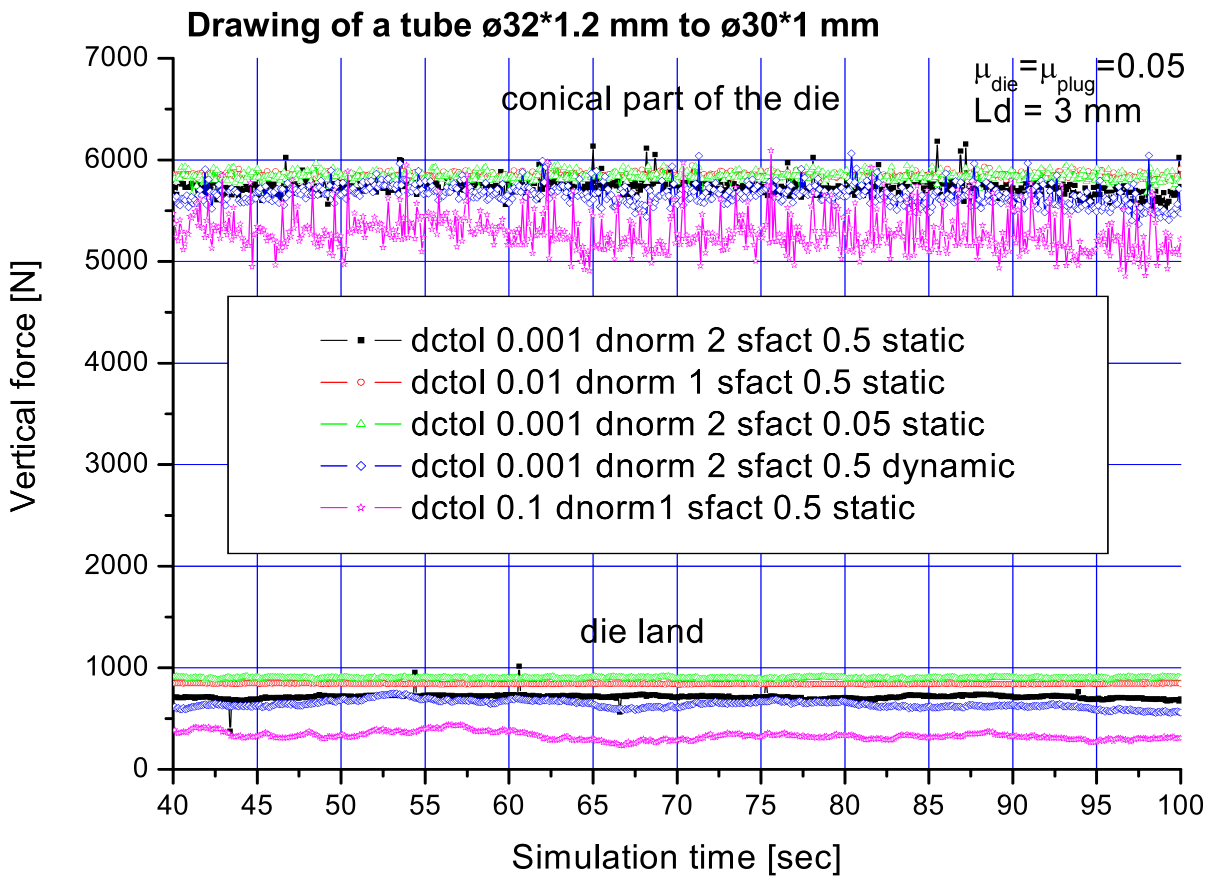

Figure 3: The vertical force on the conical part of the die and on the die land for the simulations listed in Table 1

With cof = 0 (which is the default value) the friction between the plug and the inside tube wall became so large that the plug was drawn with the tube through the die. It is the authors experience that when simulating metal forming process the best results are obtained with cof = 1.
With dctol = 0.001 (the default value) and dnorm = 1, the simulation stopped due to convergence problems. If dctol was increased to 0.01 the simulation could be carried out but the CPU time was fairly long, 142 min. Increasing dctol to 0.1 decreased the CPU time to 82 min, but the increase of dctol had a negative influence on the contact forces; the increase increased the noise in the vertical force on the conical part of the die and decrease the vertical force on the conical part of the die and on the die land.
With sfact = 0.5 the maximum node penetration in the die was less than 1 μm, which was judged to be acceptable. Decreasing sfact to 0.05 increased the maximum node penetration in the die to around 7 μm which was judged to be too large.
The simulation carried out dynamically and statically gave nearly the same results; there is slightly more noise in the force curve from dynamic simulation (see Figure 3) and the simulation time was substantially longer; 104 min versus 22 min when the simulation was carried as static.
Based on the results shown in Figure 3 it was decided to carry out the simulations with dctol = 0.001, dnorm 2, sfact 0.5, cof = 1 and as static as this choice seemed to give acceptable results and with the shortest CPU-time.

2.3 Process window with regard to friction

Simulations were carried out with the combinations of friction coefficients in the die-tube interface and in the plug-tube interface shown in Figure 4.

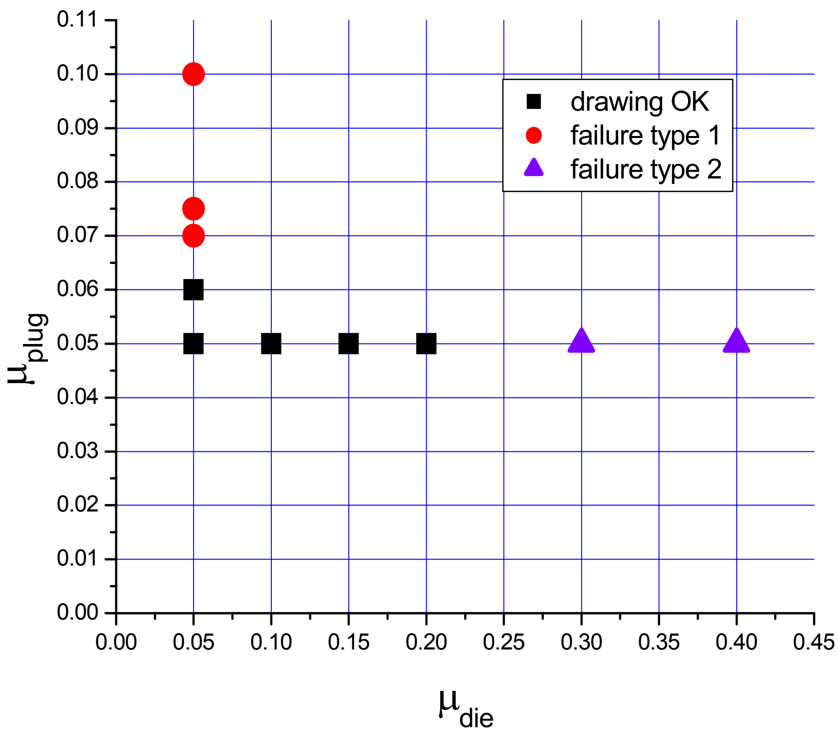

Figure 4: 2D FEM simulations of the tube drawing were carried out with the different combinations of μ_{die} and μ_{plug} shown.

The drawing could be carried out successfully when the friction coefficients were in the range $0 < \mu_{die} \leq 0.2$ and $0 < \mu_{plug} \leq 0.06$. For $\mu_{plug} \geq 0.07$ the frictional force on the plug became so large that the plug was drawn with tube through the die. This type of failure is denoted failure type 1. For the friction combinations ($\mu_{plug} = 0.05$, $\mu_{die} = 0.3$) and ($\mu_{plug} = 0.05$, $\mu_{die} = 0.4$), the drawing stress in the tube wall after passing the die became so large that the drawn tube deformed plastically (the tube diameter became smaller than the diameter of the die land); this type of failure is denoted failure type 2.
From Figure 4 it can be seen that the tube drawing is much more sensitive to the friction in the plug-tube interface (a successful drawing requires $\mu_{plug} \leq 0.06$) than in the die-tube interface (a successful drawing requires $\mu_{die} \leq 0.20$).

Figure 5 shows the tube drawing force for different combinations of the friction in the die-tube interface (μ_{die}) and in the plug-tube interface (μ_{plug}). It can be seen from Figure 5 that the drawing force increases if one of the friction coefficients increases and that the drawing force is very sensitive to changes in the friction coefficients; e.g. an increase of μ_{die} from 0.05 to 0.10 (μ_{plug} = 0.05) increases the drawing force from approximately 6400 N to approximately 7650 N; an increase in the drawing force of approximately 20%.

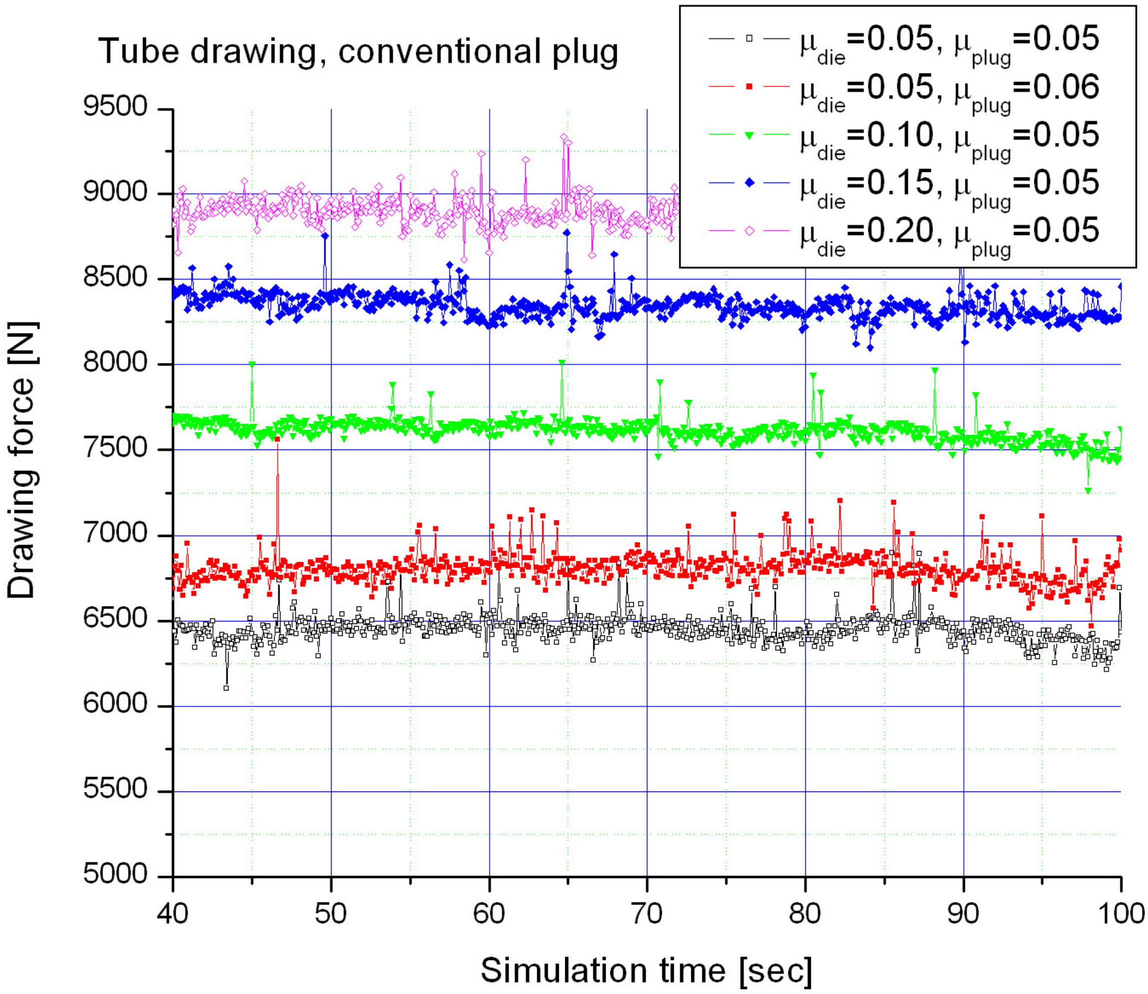

Figure 5: The drawing force for different combinations of the friction of μ_{die} and μ_{plug}.

2.4 Influence from the length of the bearing channel

To investigate the influence from the length of the bearing channel on the drawing force simulations were carried out where the length of the die land Ld was increased from 3 mm to 5 mm and 7 mm; in both the simulations (μ_{die}, μ_{plug}) was (0.05, 0.05). With Ld = 3 mm the drawing force was approximately 6400 N (see Figure 5). With Ld = 5 mm the drawing force increased to approximately 7500 N and with Ld = 7 mm, the plug was pulled through the die.

2.5 Influence from the shape of the bearing channel

To investigate the effect of slight changes in the geometry of the bearing channel simulations were carried out with the bearing channel slightly choked (($\theta = 0.1^0$, $\varphi = 0.0^0$) and ($\theta = 0.0^0$, $\varphi = -0.1^0$)) and with the bearing channel slightly relieved (($\theta = -0.1^0$, $\varphi = 0.0^0$) and ($\theta = 0.0^0$, $\varphi = 0.1^0$)) (see Figure 6). In all simulations (μ_{die}, μ_{plug}) was (0.1, 0.05). Figure 6 shows the tube drawing force with the bearing channel slightly choked (($\theta = 0.1^0$, $\varphi = 0.0^0$) and ($\theta = 0.0^0$, $\varphi = -0.1^0$)), with the bearing channel slightly relieved ((θ = -0.1^0, φ = 0.0^0) and (θ = 0.0^0, φ = 0.1^0)) and with the bearing channel being cylindrical. It can be seen that the drawing force is nearly the same independently of whether it is the plug land or the die land which is conical, but that it has a significant influence whether the bearing channel is choked or relieved; with a relieved bearing channel the drawing force is ≈ 5,700 N, and with a choked bearing channel the drawing force increases to ≈ 8,100 N; an increase of ≈ 42%. It can thus be concluded that very minor changes in the geometry of the bearing channel can have a significant influence on the drawing force; with a length of the die land Ld = 3 mm as in this investigation, the cylindricity of the die land with θ = 0.1^0 or θ = -0.1^0 is ≈ 0.01 mm. To the knowledge of the authors, drawing dies are commonly manufactured with a cylindricity tolerance in the range of 0.01 mm, and even if the dies do live up to this manufacturing specification a die change may thus give rise to a significant change in the drawing force.

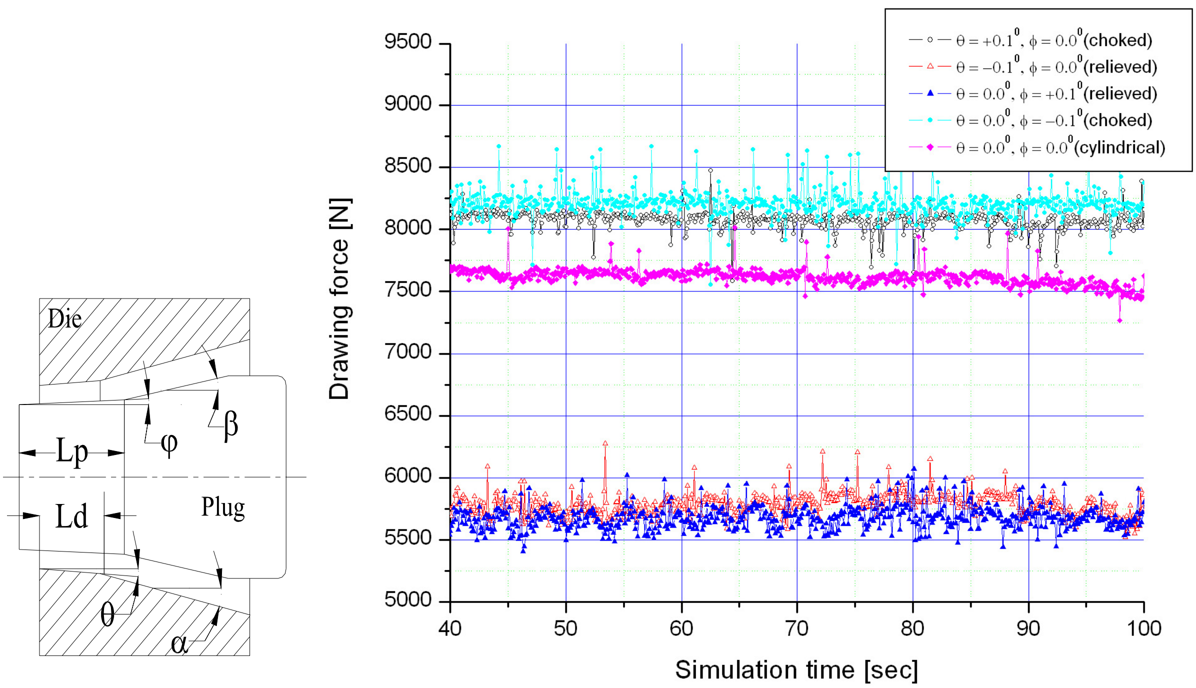

Figure 6: The drawing force with the bearing channel slightly choked, slightly relived and cylindrical

3 A new plug design

Figure 7 (left) shows a sketch of a new plug design where the conventional cylindrical plug land is replaced with a circular profiled plug land with radius R, and (right) the FEM model. The intensions with the new plug design are 1) to separate the tube sinking and the tube wall thinning as much as possible; ideally the tube thinning should only take place between the circular profiled plug land and the die land and 2) to mechanically "lock" the plug in the tube in order to reduce the tendency to plug chatter.

3.1 The influence from friction

Simulations with the new plug with R = 4 mm were carried out for the same combinations of friction conditions in the die-tube interface, μ_{die}, and in the plug-tube interface, μ_{plug}, as simulated with the conventional plug, see Figure 4, and the results obtained are shown in Figure 8. Besides from the geometry of the plug everything was identical to the simulations carried out with the conventional plug.

From Figure 8 it can be seen that the tube drawing with the new plug could be carried out successfully for the friction combinations (μ_{die} = 0.05, μ_{plug} = 0.05, 0.06, 0.7, 0.75). For (μ_{die} = 0.05, μ_{plug} = 0.1), the tube became squeezed between the plug and the die and the drawing failed (failure type 1). For the friction combination (μ_{die} = 0.4, μ_{plug} = 0.05) the drawing force became so large that the drawn tube deformed plastically after passing the die (failure type 2). The simulations thus show that the tube drawing also with the new design is more sensitive to the friction in the plug-tube interface (successful drawing requires $\mu_{plug} \le 0.075$) than in the die-tube interface (successful drawing requires $\mu_{die} \le 0.30$), and that the drawing can be carried out successfully for larger values of μ_{die} and μ_{plug} than with the conventional plug, see Figure 4.

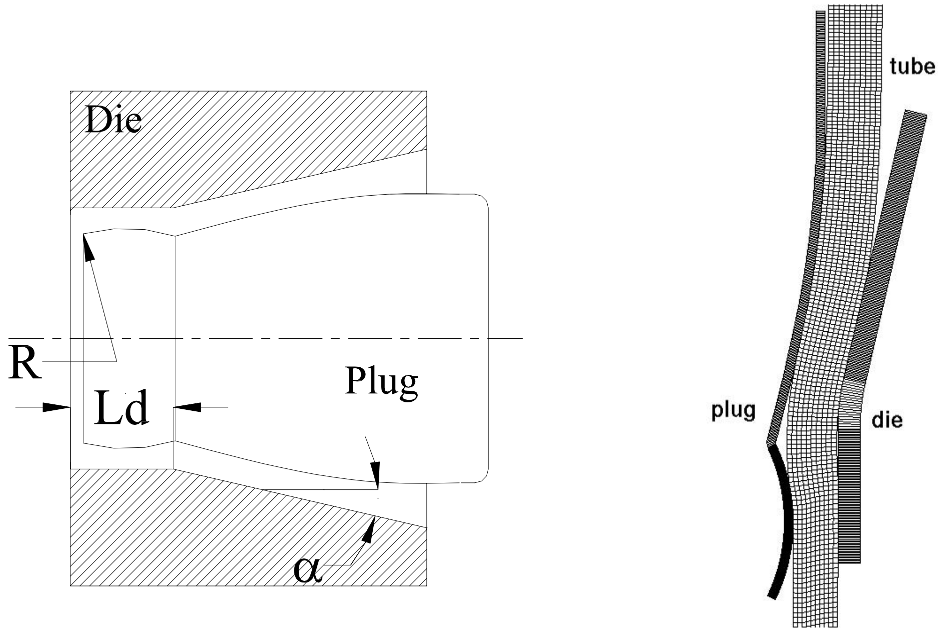

Figure 7: Left: sketch of the new plug design. Right: FEM model of the tube drawing with the new plug design

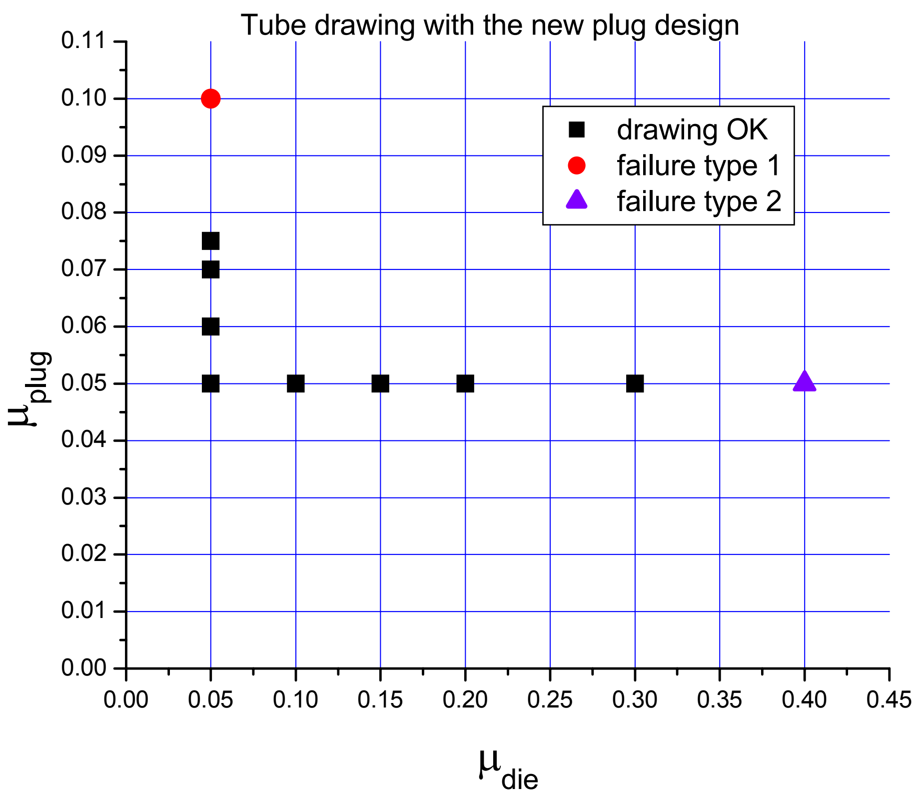

Figure 8: 2D FEM simulations (rotational symmetric) of the tube drawing with the new plug design were carried out with the friction combinations shown. The symbols show when the drawing could be carried out successfully and when the drawing failed

Figure 9 shows the tube drawing force with the new plug design for same friction combinations as in Figure 5 with the conventional plug design. It can be seen that drawing force is very sensitive to changes in the friction in the die-tube interface; e.g. an increase of μ_{die} from 0.05 to 0.1 (with μ_{plug} = 0.05) increases the drawing force from approximately 5500 N to approximately 6200 N, an increase of approximately 13%. Comparing the drawing forces with the conventional plug design, Figure 5, and the drawing forces with the new plug design, Figure 9, it can be seen that the drawing force with the new plug design is substantially lower than with the conventional plug design; e.g. for the friction combination (μ_{die}, μ_{plug}) = (0.1, 0.05) the drawing force with the conventional plug is approximately 7,600 N whereas it with the new plug design is approximately 6,200 N.

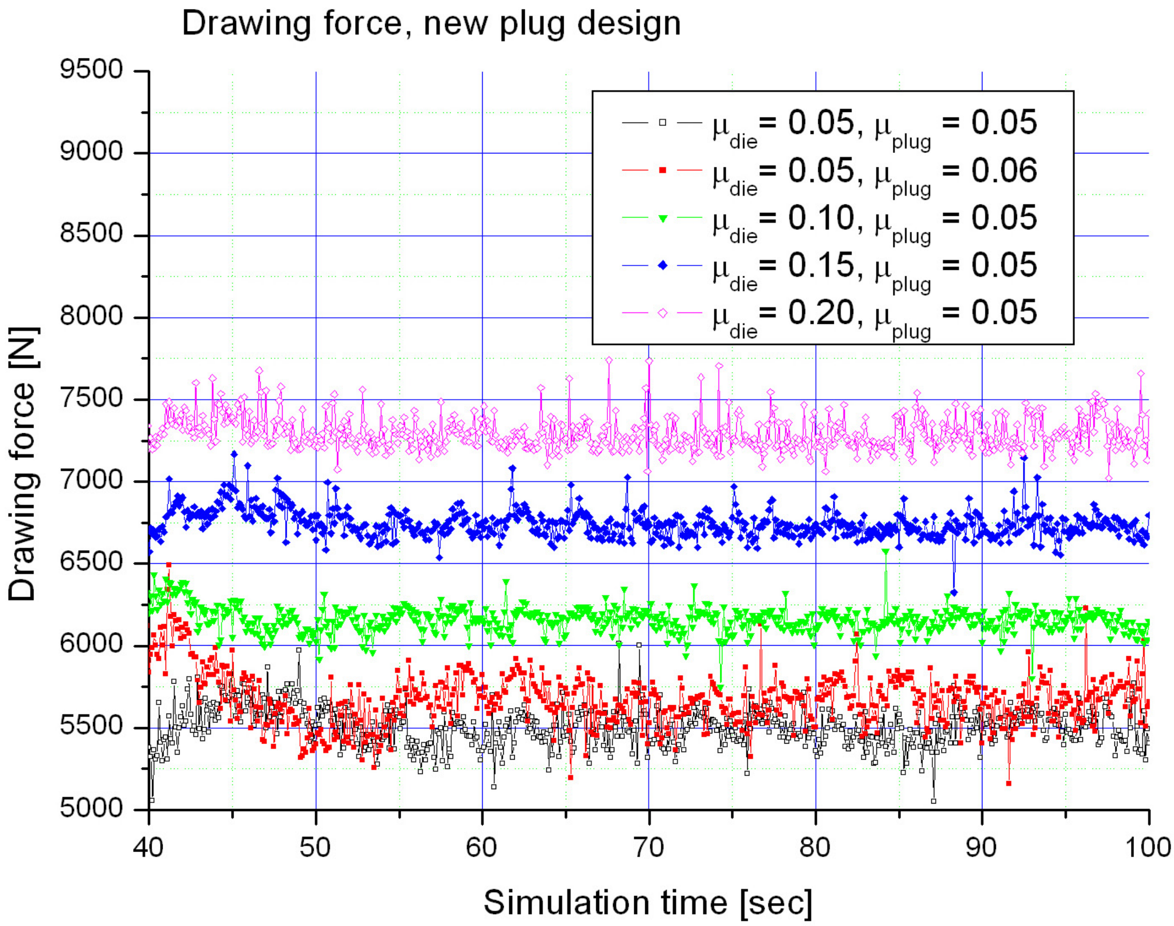

Figure 9: The tube drawing force with the new plug design for different combinations of the friction coefficients μ_{die} and μ_{plug}

3.2 Influence from the die land angle and the length of die land

Simulations were carried out with the angle of the die land θ = -0.1^0, 0.1^0 and 0.0^0 (see Figure 10) and the results obtained for the tube drawing force are shown in Figure 10. It can be seen that with the new plug design a small change in the die land angle has nearly no influence on the tube drawing force. The simulations thus suggest that the tube drawing carried with the new plug geometry is more robust with regard to small variations in the geometry of the die land than when carried out with the conventional plug, where a slight variation in the die land angle can give rise to a significant change in the tube drawing force.

A simulation was also carried out with the length of the die land Ld = 5 mm instead of 3 mm. Increasing the die land length to 5 mm had nearly no influence on the tube drawing force.

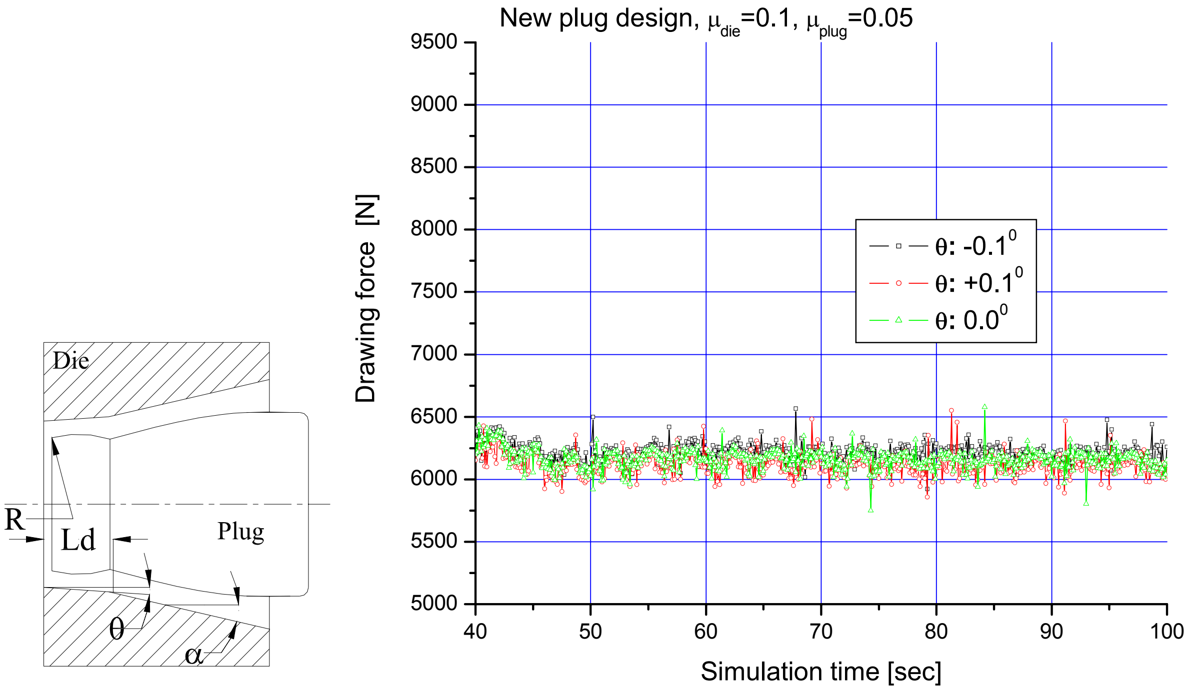

Figure 10: The drawing force with the die land angle θ = -0.1⁰, 0.1⁰ and 0.0⁰.

3.3 Self-catching plug

Tube drawing with a floating plug is a highly automated process. However the threading (or starting) of the process is mainly done manually as follows:

- a certain amount of lubricant is filled into the tube
- the plug is inserted in the tube
- the front end of the tube is tapered e.g. using rotary swaging
- a dent is made in the tube behind the plug
- the tapered front end is feed through the die and gripped by a gripper arrangement

The dent in the tube behind the plug is necessary to bring the plug into the correct position (the equilibrium position) in relation to the die. Without a dent the plug will be pushed ahead of the die and no reduction of the tube wall thickness will take place between the plug land and the die land. The dent is commonly made manually with a hammer and making the dent is difficult. If the dent is not made big enough the plug may pass the dent without being brought in the right position in relation to the die and if the dent is made too large the dent may lead to tube fracture. To ease the threading process it is suggested to make the plug wit a conical front end as shown in Figure 11.

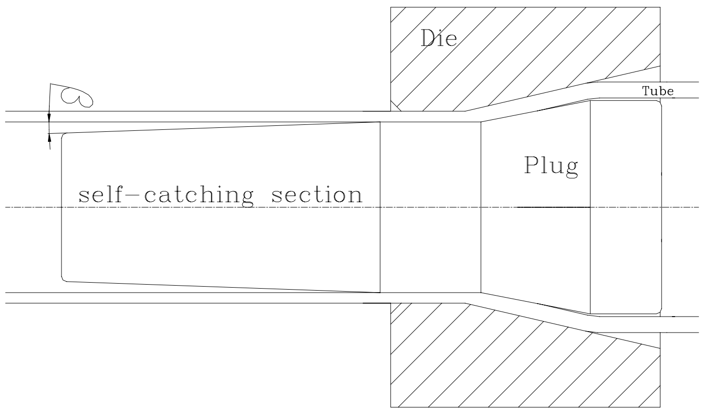

Figure 11: A self-catching plug. During start up the friction between the conical front end (self-catching section) and the tube wall will bring the plug into the right position in relation to the die

The angle β is made so small that $\mu > \tan(\beta)$ where μ is the friction coefficient between the conical front end and the inside of the tube wall. Provided that the relation $\mu > \tan(\beta)$ is fulfilled the frictional force between the conical front end of the plug and the tube wall will pull the plug into the right position in relation to the die; there is thus no need to make a dent in the tube behind the plug. Figure 11 shows conventional plug geometry with a conical front end (self-catching section). A conical front can of course also be applied to the new plug geometry, Figure 7, making the new plug design self-catching.
That the self-catching plug works (that is the frictional force between the conical self-catching section and the tube wall brings the plug into the right position in relation to the die during start up) has been verified experimentally in laboratory tests and using FEM simulations. The simulations were carried out as 2D rotational symmetric. The friction coefficient in all interfaces was $\mu = 0.05$ and the angle β was 2^0; $\tan(2^0) = 0.034$ and the condition $\mu > \tan(\beta)$ is thus fulfilled.
Figure 12 shows the FEM simulation at different stages during the start up. In Figure 11 a the self-catching section of the plug has just come into contact with the inside tube wall. In Figure 11 b the plug is nearly drawn into its final position. In Figure 11 c the plug has been drawn into its final position and the tube drawing process has become stationary.

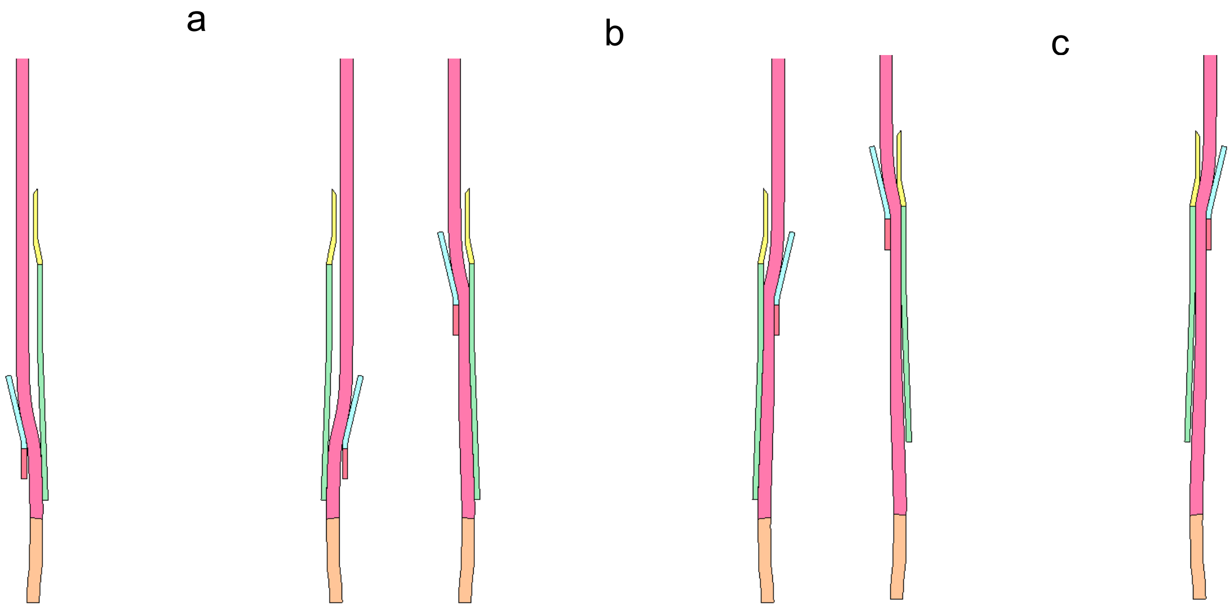

Figure 12: Different stages during start up with the self-catching plug. a) just after the self-catching section of the plug comes into contact with the tube wall, b) the plug is being drawn into position, c) the plug has been drawn into position and the drawing process has become stationary

Figure 13 shows the tube drawing force as function of the drawing distance during start up with the self-catching plug. At a drawing distance ≈ 10 mm (the situation shown in Figure 11 a) the inside tube wall comes into contact with the self-catching section of the plug and after ≈ 28 mm (the situation shown in Figure 11 c) the plug has been drawn to the final position in relation to the die. From ≈ 28 mm and onwards the tube drawing process is stationary.

It is worth noticing that there is nearly no overshoot in the tube drawing force when the plug reaches its final position in relation to the die after ≈ 28 mm. In common tube drawing with a floating plug where the plug is brought in the right position in relation to the die by making a dent in the tube behind the plug, there is an overshoot in the tube drawing force due to the dent (compared to the stationary tube drawing force).

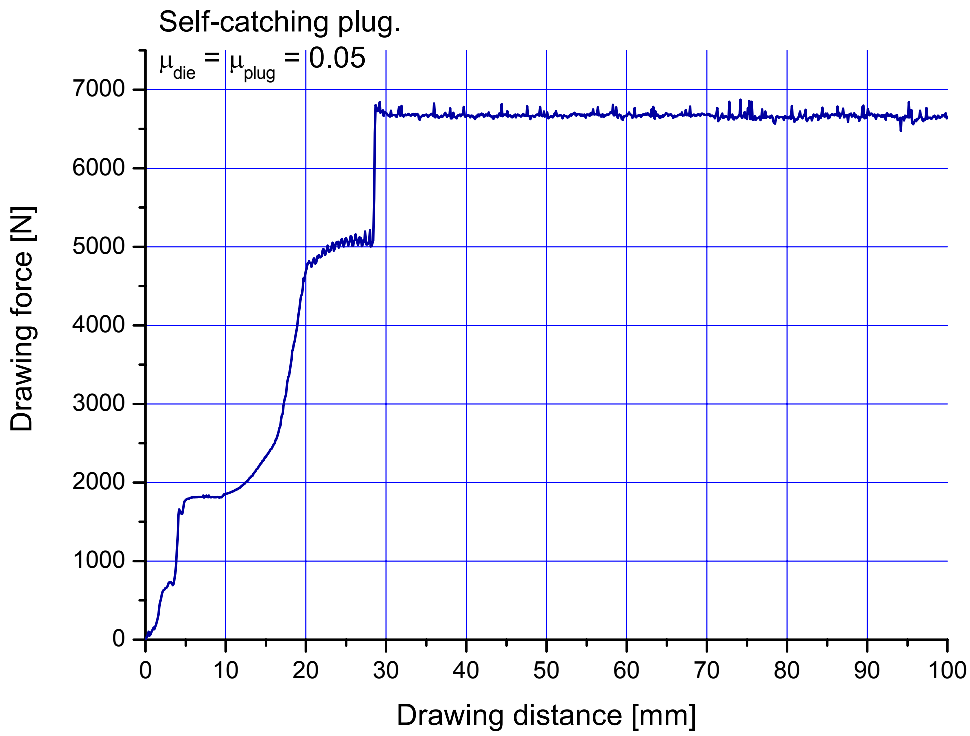

Figure 12: The tube drawing force as function of simulation time during start up with the self-catching plug

4 Conclusions

The drawing of a tube with a floating plug, from ø32*1.2 mm to ø30*1.0 mm has been analyzed using 2D rotational symmetric simulation.
When the drawing is carried out with a conventional die and plug, the simulations show

- that the drawing is very sensitive to the friction, especially in the plug-tube interface. The drawing could be carried out successfully with $\mu_{die} \leq 0.20$ and $\mu_{plug} \leq 0.06$.
- that the shape of the bearing channel has a significant influence on the drawing force. If the bearing channel is slightly choked the drawing force is approximately 42% larger than when the drawing channel is slightly relieved.

A new plug design has been proposed. The new plug has a circular profiled plug land (conventionally the plug land is cylindrical). The intensions with the new plug design are 1) to separate the tube sinking and the tube thinning 2) to mechanically lock the plug in the tube. 2D simulations of tube drawing with the new plug design show

- that the drawing can be carried out successfully with $\mu_{die} \leq 0.075$ and $\mu_{plug} \leq 0.30$. This process window with regard to friction is thus larger with the new plug than with the conventional plug.
- that the drawing force is less with the new plug design compared to the conventional plug design. With the new plug the drawing force is approximately 6,200 N for (μ_{die}, μ_{plug}) = (0.05, 0.05) compared to approximately 7,600 N with conventional plug.
- that the drawing force is nearly independent of small changes in the die land angle.

It is suggested to make the plug self-catching during start up by making the plug with a conical front end. Simulations show that during start up friction between the conical front end and the inside tube wall will bring the plug in the right position (the equilibrium position) in relation to the die, and that there is nearly no overshoot in the drawing force during start up. Making the plug self-catching eliminates the need to make a dent behind the plug and also reduces the risk for failure during start up (tube breakage if the dent behind the plug has been made too large or the plug is pushed ahead of the die if the dent has been made too small). It has also been verified experimentally that the self-catching plug works.

5 Literature

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