RESIDUAL STRESS ON STAINLESS STEEL A304 TUBE DRAWN WITH FIXED PLUG

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Abstract. *Tubular components that present compressive residual stresses in their inner surface can be used as mechanical parts to improve their resistance to torsion and bending cyclic stresses. Tube drawing with internal plug can induce this kind of residual stresses. The main objective of this work is to present a cold drawing tool set designed to generate these compressive residual stresses within stainless steel A304 tubes, and concurrently reduce the drawing loads. This work also presents an indirect experimental procedure to determine these stresses, since the conventional x-ray diffraction method used to measure them demands a planar surface. Tube drawing was simulated by the finite element method. Experimental tests with the tube drawing tool set were also carried out with fixed plugs to analyze the influence of the lubricant, drawing speed and lubrication regimes on the drawing load. Experimental results were compared to numerical results to validate these models and to define the best drawing conditions. These results showed that the x-ray diffraction method used in this work is reliable to determine the residual stresses. It was also shown that the tube drawing tool set was efficient to reduce the drawing load and to generate compressive residual stresses in the inner surface of the drawn tubes.*

Keywords*: Tube drawing, Residual Stresses, Lubrication, Analytical Methods, Finite Element Method.*

1. Introduction

Wire drawing is an important metalworking process because it can produce parts with good finished suface and improved mechanical properties. Tube drawing can be carried out with or without an internal tool. In the second case, the tool is used to provide a better-finished surface than the obtained without internal tool (Avitzur, 1983). It can be supposed that this tool will induce compressive residual streess in the inner tube surface. Tubes with residual compressive stress on its inner surface can be used as mechanical element such it is more resistant to torsion and bending cyclic stresses (Blazynski, 1986, Brethenoux, 1996).

In this work we present a tool set which proved to be able to promote an efficient lubrication in the tools-workpiece interface, reducing drawing force and creating a tube internal surface with compressive residual stress.

To analysis residual stress we used the x-ray diffraction method (He, 2003). However, the method is applied to planar surfaces, which is not the case of the tube internal surface. Therefore we proposed an indirect experimental procedure to evaluate the residual stress. A piece of tube after drawing was cut of on its longitudinal axis, and then deformed by flat tools to be planed (Prevey, 1986). The residual stress induced by this procedure was simulated by the Finite Element Method (FEM) and the numerical result was added to the results obtained by x-ray diffraction method in order to obtain a prediction of residual stress.

The tube drawing with fixed plug was simulated by the Finite Element Method to obtain a prevision of the residual strees. The results were compared to those obtained by the indirect method previously presented (Karnezis and Farrugia, 1998, Pospiech, 1998).

Experimental test were carried out with different drawing speeds, lubrication regimes and lubricants. The results statistically analyzed showed the best condition to reduce drawing force, combined to higher compressive residual stress.

2. Methods and materials

2.1. FEM simulation

Tube drawing process was simulated with the software MSC.Superform 2002 using a 3D finite element model as shown in Fig. 1. Tubes with dimension 10 x 1.5 mm (diameter x thickness) were drawn to three diferent area reduction, using four die angles for each reduction. In all simulations, the wall thickness was reduced from 1.5 mm to 1.4 mm.

A quarter piece of tube 100 mm long was modeled using a number of 3200 brick elements with 8 nodes to define the mesh. This length was tested in order to obtain the steady-state condition. The die geometry presented a 30º half entry angle, a 15º half exit angle and bearing length of 0.4 times the outlet dameter.

Friction coefficient between die and tube and between tube and plug was estimated as 0.05, assumed to be Coulomb friction. Die and plug were modeled with an elastic material, assumed to be tugsten carbide (Young modulus of 700 GPa).

An elasto-plastic model was used for the material of the tube. Tensile tests of stainless A304 steel tube were hold to obtain the stress-strain curve (σ x ε) applied to the simulation. This stress-strain curve was approached by Holloman's equation as shown in Eq. (1). The values obtained to Holloman's equation (K, n) are typical to this kind of material.

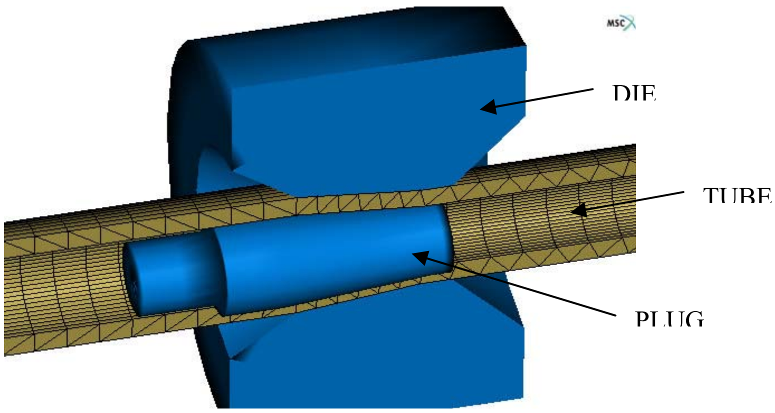


Figure 1 – FEM meshes of tube, die and plug used in the numerical simulation

$$\sigma = 1137\ \varepsilon^{0,52}\ \text{[MPa]} \qquad (1)$$

Young modulus of 210 GPa and a Poisson ratio of 0.3 were considered to the tube material, which was assumed to be isotropic and insensitive to strain rate. During experimental drawing tests it was noticed that the temperature at the tube was not higher than 100 ºC, thus allowing the tube material to be modelled as a material independent on the temperature.

2.2. Experimental tests

Stainless steel AISI 304 tubes were drawn in a laboratory drawn bench. Tubes with 10 x 1.5 mm (diameter x thickness) were reduced to 7.94 x 1.4 mm, which represents a drawing pass with 34.4% of area reduction. Two dies were used; both made of tungsten carbide with die semi-angle of 7º and bearing length of 3 mm. One die has an exit diameter of 9.8 mm and the other an exit diameter of 7.94 mm. Figure 4 shows an illustration of the die support used.

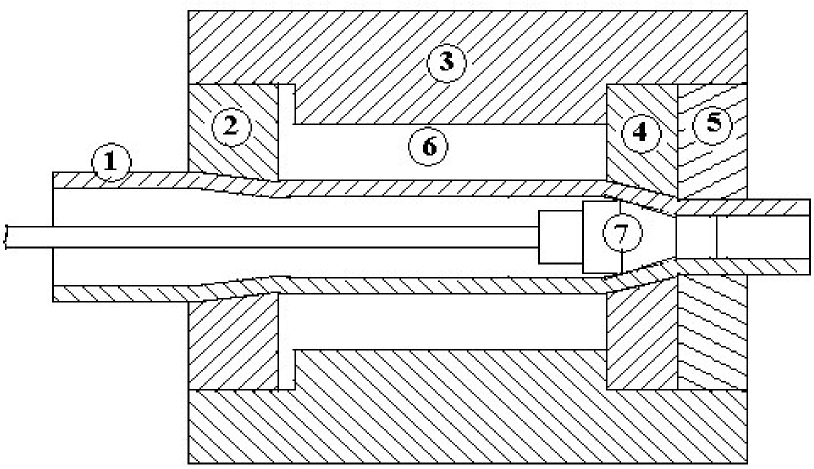


Figure 4 – Schematic representation of the die support dies and tube.

In Fig. 4:
1 – tube
2 – first reduction die
3 – die support
4 – second reduction die
5 – load cell
6 – pressure chamber
7 – fixed plug

The tube initial length was 500 mm. Before the drawing tests the tubes were cold swaged to reduce one of its ends to allow them to pass through the dies.. After the tube was located inside the die, the die support was filled with oil and closed to pressurize the chamber.

Tubes were drawn at speeds of 1.0, 2.0 e 5.0 m/min and three lubricants were used: a common mineral oil SAE 20W50 (22 cSt at 100 ºC), Renoform MZA-20 (190 cSt at 100 ºC), a mineral oil formulated with extreme pressure additives and grease, indicated to cold forming processes and *Extrudoil 319 MOS* a semi-sintetic oil, without chlorine with MoS_2, used to cold forming

Plug was made of AISI D6 tool steel, quenched and tempered to 52 HC. Plug semi-angle was 5.4º with a nib length of 2 mm. Tube cavity was filled with the same oil used in die support, and then the plug was positioned at the work zone and fastened by a stick to the drawn bench structure.

A cylinder forms plug geometry, a region to position the plug inside the die. Its diameter is slightly smaller than the tube inner diameter. The plug semi-angle is smaller than the die semi-angle (α). It is suggested to be 2 degrees or more smaller than the die semi-angle (Avitzur, 1983 and Pawelsky, O. and Armstroff, O., 1968). A third region, called 'nib', is cylindrical and controls the inner diameter of the tube. In the present study the wall thickness of the tube was reduced of 0.1 mm. The length of the nib was fixed on 2 mm for all tests.

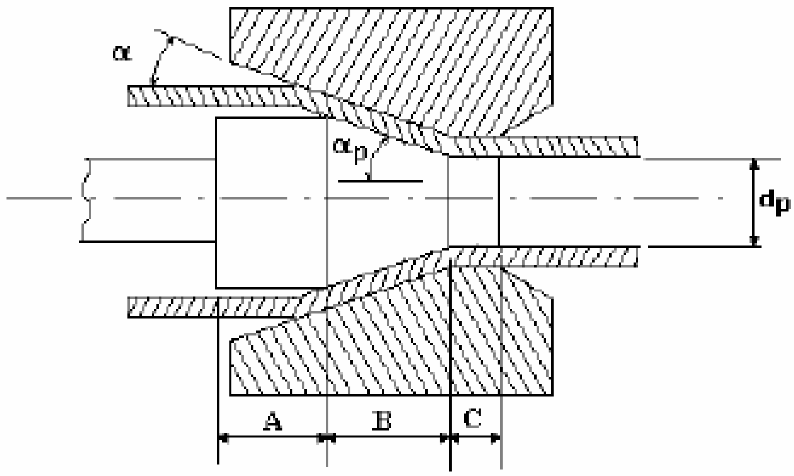


Figure 3 – Plug geometry

Two lubrication regimes were obtained. When the tube was drawing with the tool set, the first reduction die was pulled to increase the oil pressure. The oil is forced to pass thorugh the second recuction die with the tube and, therefore, friction is reduced. When the end of the tube passed through the first reduction die, the pressure chamber results openned. The pressure fell down to the atmospheric pressure and friction on the second reduction die was then increased.

2.3 X-ray diffraction tests.

Tube was cutting on 20 mm long and sectioned to exposed its inner surface. The samples, one for each drawing speed combined to each lubricant, was then pressed between flat tools, to obtain a plan surface. The nine samples were submit to x-ray diffraction to obtain the residual stress. A tenth sample, cuttig from a non-deformed tube was used to be the reference sample.

2.4. FEM planed surface simulation

The procedure to plan samples to x-ray diffraction was simulated to estimate the residual stress induced as shown in Fig. 4.

A bi-dimensional model of the 10 x 1.5 mm (diameter x thickness) middle tube section was generated wtih 495 isoparametric elements with 4 nodes The mechanical behavior of the material was the same used to FEM simulation of tube drawing.

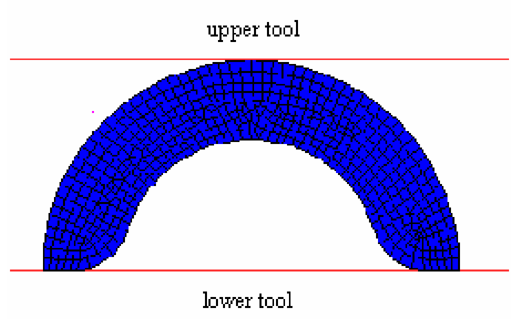
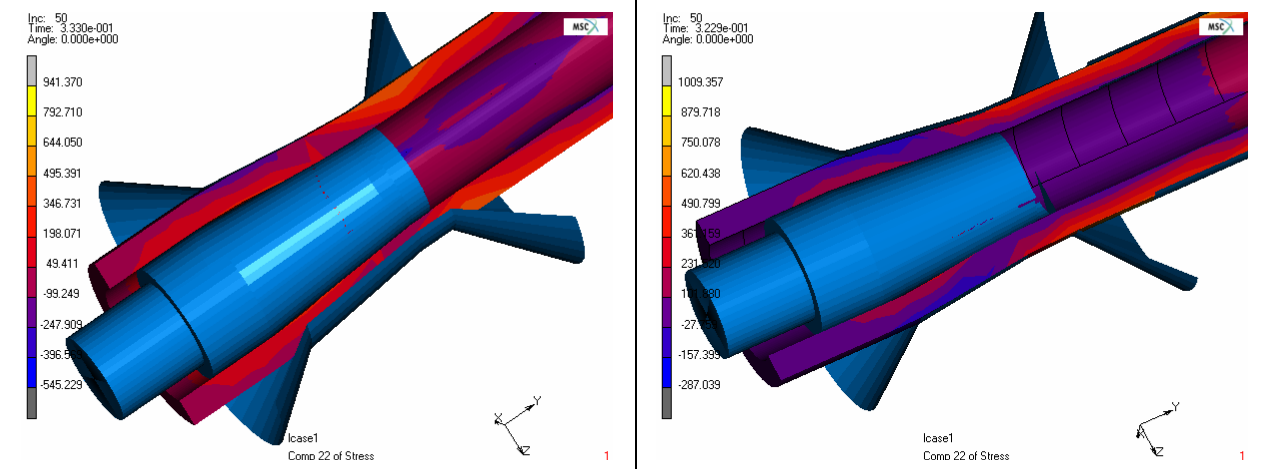


Figure 4 – Model to sample pressing to x-ray difraction

3. Results and discussion

3.1 Results from tube drawing simulation

Figure 5 shows the results obtained to longitudinal stress by the Finite Element Method, where µ1 is the friction between die and tube and µ2 is friction between plug and tube. It can be seen clearly the increase of tension on the internal surface of the tube after drawing when the friction between plug and tube increases.



(a) µ1 = 0,05; µ2 = 0,05 (b) µ1 = 0,05; µ2 = 0,1

Figure 5 – Equivalent stress by FEM – die semi-angle = 7^0

Figure 6 shows the Equivalent stress of a point located on the inner tube surface. The point position varies from the die inlet till 40 mm far from it. Curve 1 refers to case (a) and Curve 2 to case (b) mentioned on previous pragraph. It can be seen that both models presented the same behavior. The drawing longitudinal stress increases and it is unstable till the point reaches 10 mm. From that position ahead, the stress becomes constant and stable.

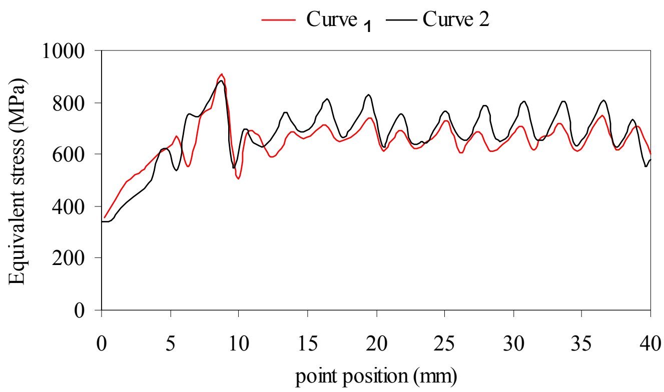


Figure 6 – Longitudinal drawing stress – FEM results.

Figure 7 shows the residual stress on inner surface for case (a), obtained by simulation FEM. This figure shows the tube when it was just passed through the entire die and then relieved. Residual stress value is compressive and about 755 MPa.

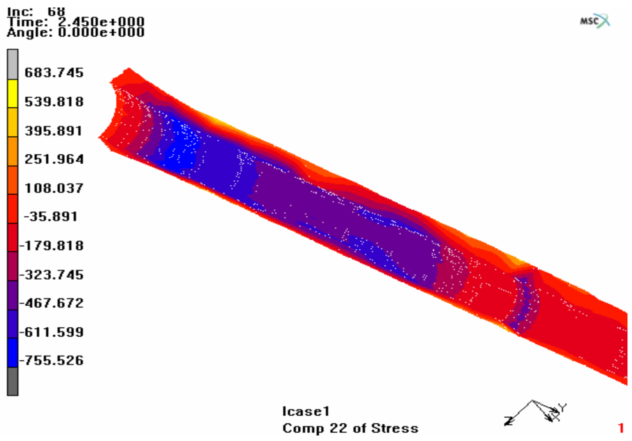


Figure 7 – Residual drawing stress - FEM results.

3.2. Experimental tests results

Results of experimental tests are shown in Figs. 8 to 10. Each curve represents the mean drawing force obtained from three observations for tube drawing with fixed plug.

Figure 8 shows the curves of mean drawing force using as lubricant the mineral oil SAE 20W50. Curve 1 is the mean drawing force for drawing speed of 1 m/min. Curves 2 and 3 shows the mean drawing force to drawing speed of 2 m/min and 5 m/min, respectively.

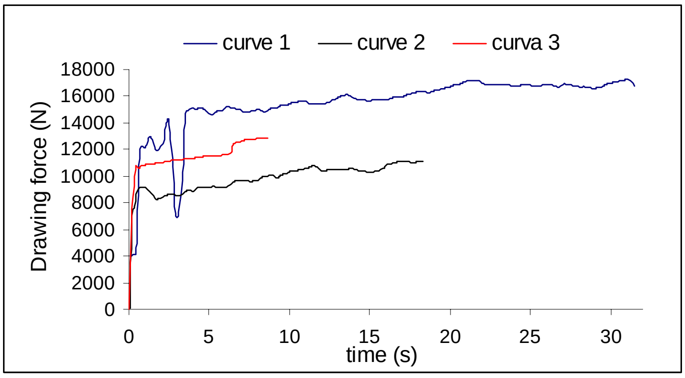


Figure 8 – Mean drawing force – lubricant: mineral oil SAE 20W50

As Figure 8 shows, the drawing force increases fast and becomes quite steady. The drawing speed presents an important influence on drawing force. Curve 3 shows an increase on drawing force at the end of the drawing process. It occurs when the tube end pass through the second reduction die and the chamber pressure is reduced to atmospheric pressure. At this moment, lubrication becomes worst and friction increases.

Figure 9 shows the mean drawing force when Renoform MZA 20 is used as lubricant. Here, again, curve 1 refers to drawn speed of 1 m/min, and curves 2 and 3, to 2m/min and 5 m/min, respectively.

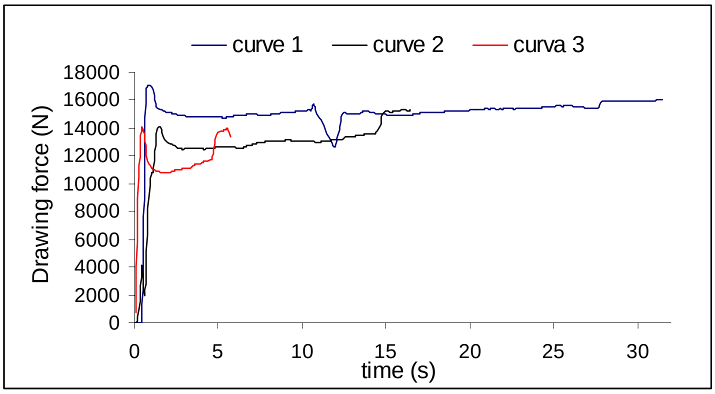


Figure 9 – Mean drawing force – lubricant: Renoform MZA 20

The effect of pressure can be seen more clearly on curves 2 and 3. The effect of drawing speed on drawing force is more pronounced than that related to the mineral oil SAE 20W50.

Figure 10 shows the mean drawing force when we use Extrudoil 319 MOS, combined to drawing speed of 1, 2 and 5 m/min, represented by curves 1, 2 and 3, respectively. Again the pressure effect can be observed. However, drawing speed do not influence too much the drawing force.

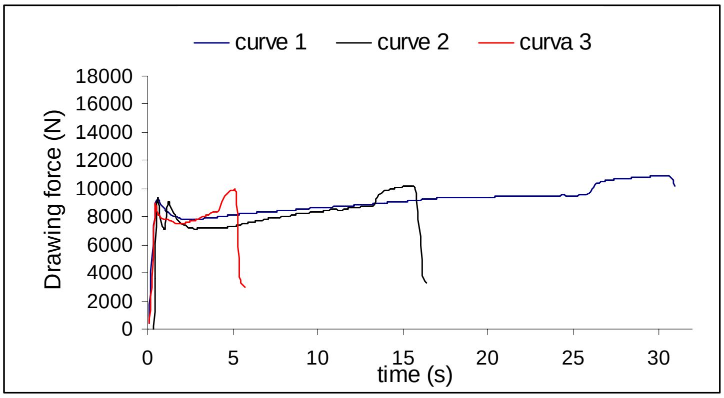


Figure 10 – Mean drawing force – Lubricant: Extrudoil 319 MOS

Table 1 shows the values of mean drawing stress in all cases. Drawn stress is obtained considering the cross section area of drawn tubes.

Table 1 – Mean drawing stress (MPa)

Lubrication	SAE 20W40		
	1 m/min	2 m/min	5 m/min
Pressurized	450,0	273,8	328,3
Without pressure	498.7	308,2	358,8
	RENOFORM MZA 20		
	1 m/min	2 m/min	5 m/min
Pressurized	448,3	374,1	323,0
Without pressure	445,0	435,2	358,7
	EXTRUDOIL 319 MOS		
	1 m/min	2 m/min	5 m/min
Pressurized	266,3	229,3	228,2
Without pressure	310,7	272,7	285,1

3.3. FEM plan surface simulation results

Results of simulation procedures to plan the tube surface shows that when the flat tools finished to work and are retrieved, there is a tractive residual stress about 208 MPa on the planned surface.

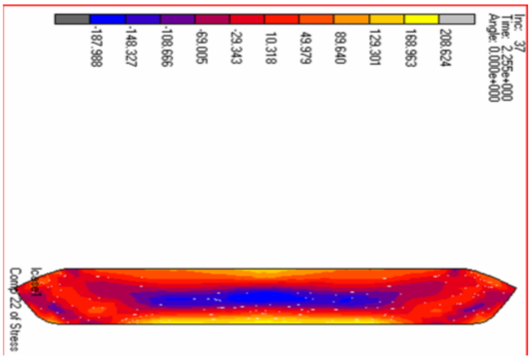


Figure 11 – FEM pressed surface simulation

3.4. X-ray diffraction results

Figure 12 shows the x-ray diffraction intensity of analyzed samples. It can be seen the peaks of diffraction intensity correspondent to the characteristics angles of stainless steel A304.

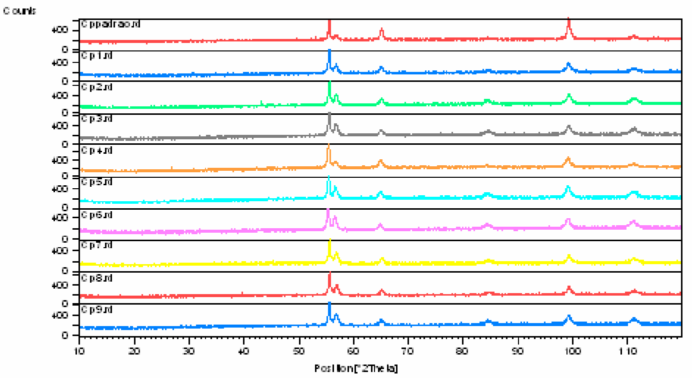


Figure 12 – Xray difraction intensity.

Results of x-ray diffraction are shown on Table 2. Residual stress was obtained from the difference between interplanar distance (D) of a reference sample (Cp reference – D = 1,269537 Å) and samples from drawn tubes. Final residual stress is obtained by adding the residual stress from plan surface simulation to residual stress from x-ray diffraction. Residual stress condition informs the nature (compression or traction) of the residual stress.

Table 2 – Results form X-ray difraction and final residual stress obtained by FEM

Workpiece #	Lubricant	Drawing speed	D (Å)	X-ray Residual stress - MPa	Final residual stress - MPa	Residual stress
cp1	*SAE 20W50*	1m/min	1,270395	515,8	723	compression
cp2		2m/min	1,269864	-141,7	67	compression
cp3		5m/min	1,27014	23,9	231	compression
cp4	*Renoform MZA 20*	1m/min	1,270875	465,8	673	compression
cp5		2m/min	1,27048	228,2	436	compression
cp6		5m/min	1,270985	531,4	739	compression
cp7	*Extrudoil MOS 319*	1m/min	1,269401	-419,8	-211	traction
cp8		2m/min	1,269619	-288,9	-8	traction
cp9		5m/min	1,270056	-26,4	182	compression

According to Table 1, the conditions that results lowest mean drawing stress was that uses. According to Table 2, as expected, all conditions of tube drawing produce compressive residual stress, except the conditions related to cp7 and cp8. Conditions related to cp1, that is mineral oil SAE 20W50 and drawing speed of 1 m/min, that generate the worst lubrication and the higher drawing force, resulted in high compressive residual stress. That was anticipated by FEM simulation (see Figure 7). Then, from this association, the best condition is that related to the lubricant Extrudoil 319 MOS, a drawing speed of 5 m/min and the pressurized lubrication regime, when the drawn stress is the lowest and there are compressive residual stresses on inner surface of drawn tubes.

4. Conclusions

- Tool set was able to induce pressurized lubrication and to reduce drawing force whatever the lubricant or drawing speed.;
- with a plug fixed, compressive residual stress was generated on the internal surface of the drawn tube;
- Model generated to FEM analisys showed to be good to define this residual stress;
- the indirect method presented to obtain residual stress in the curved internal surface of the drawn tube can be used with good agreement to the results predicted by FEM analisys;
- the best test conditions were associated to the lubricant Extrudoil 319 MOS, with a drawing speed of 5 m/min and the pressurized lubrication regime

5. Acknowledgement

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