ALTERNATIVE PROCESS FOR UNCONVENTIONAL FORMING OF JUNCTION IN THIN-WALLED METAL TUBES

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Abstract: Forming of metals using elastomers has been studied in ITA (Aeronautic Technological Institute) for more than two decades, through the development of tube bending techniques, deep-drawing and forming of junctions. In relation to forming of junction in thin-walled tubes using elastomers, which is the subject of this research, several works were done along the past decade. The purpose of this work is to investigate the important parameters to the forming process throught the use of elastomer to obtain T-Junctions , such as friction, anisotropy and initial strain-hardening of the tube, aiming to obtain a better agreement between the experimental values and the analytic solution. For total forming force forecasting, it will be used the upper-bound theory and for better understanding on the anisotropic behavior of the material, it will be employed the quadratic yelding criterion proposed by Hill. The employed material for such investigation was copper. Further, it was developped a computational package using the software Matlab in order to make the graphical analyses of the results.

Keywords: *tubes thin-walled, elastomer rod, anisotropy, upper-bound theory*

1. Introduction.

In the last years with the globalization, the industrial competitivety has mobilized engineers and scientists in order to rationalize the industrial production, thus obtaining quality and competitive products both in the national as well as in the international markets. Following this line, new unconventional manufacturing processes have being developed in order to optimize products manufacturing where conventional processes become unviable from the economic point of view.

With the development of synthetic elastomers such as polyurethane, urethane and plastiprene , several articles were published using the elastomer metal forming technique, *e.g.*, metal sheet deep-drawing (Al-Quereshi, 1972; Maslennikov, 1946), tube bending and piercing (Derweesh and Mellor, 1969; Al-Quereshi and Mellor, 1967; Limb et all, 1970; Al-Quereshi, 1971), and thin-walled tubes 'T'-junction forming. Concerning to the thin-walled tubes junction forming, several works have been published along the past decade (Marreco, 1979; Moreira Filho, 1984'Moreira Filho 1986; Moreira Filho 1998).

The assumption that every material remains isotropic during the forming process is weak, since when individual crystalline grains are stretched in the higher tensile strain direction, the sample texture acquires a preferential direction, (Hosford and Caddel, 1983). In metals, the main reason for anisotropic plastic properties is this preferential direction, which arises due to grain rotation during sliding or twinning development.

Generally, the normal plastic anisotropy, R, is one of the most important parameters, being more often discussed upon the plastic yielding of anisotropic materials behavior analyses. As a consequence, the shape of the yielding locus shows a substantial changing, requiring that the anisotropic materials yielding functions include parameters characterizing anisotropy, (Hill, 1948; Lee and Backofen, 1966; Menezes, 1995).

In this work, important parameters for the forming process using elastomers to obtain 'T'-junctions, such as friction, anisotropy, and tube initial strain-hardening , were investigated aiming to obtain a better agreement between experimental values and the analytical solution.

2. Experimental Procedure

A special forming machine was designed, built and automated in order to obtain a simultaneous charge on both tube ends. The equipment consists basically of a rigid frame structure shown in Fig. (1.a), with 30 tons hydraulic cylinders on both sides, activated simultaneously during the forming process. Figure (1.b) shows an example of a 'T'-junction built through this forming process.

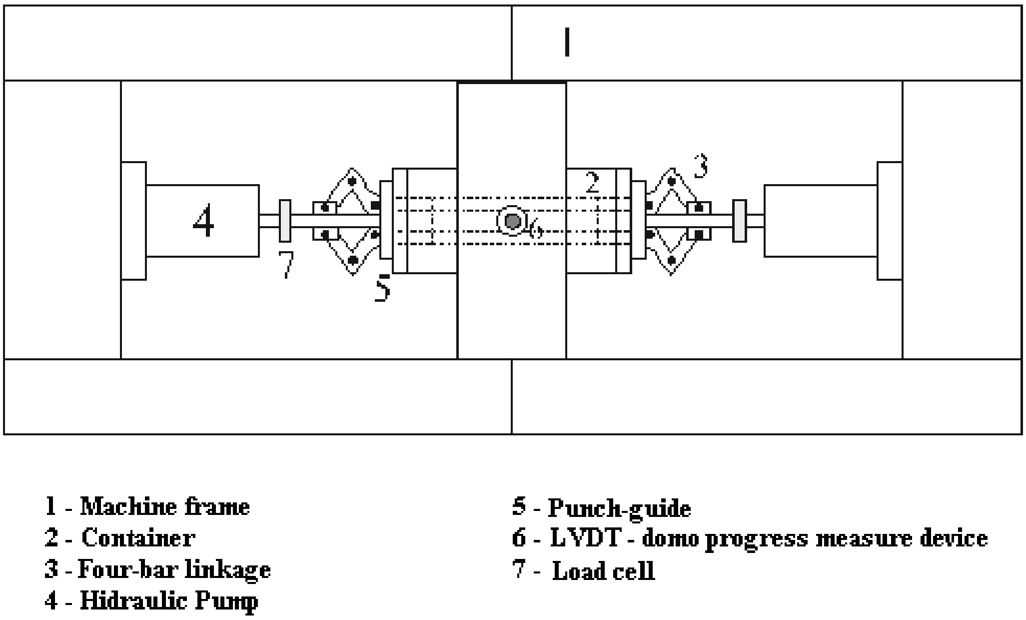

Figure 1 a. Schematic diagram of the tube machine

Figure 1.b. ‘T’-junction

3 Theoretical Model

According to the Upper Bound Theory, the existence of a cinematically admissible velocity field is assumed such that the loads responsible by the formation of this field constitute an upper bound to the loads required for the real solution. The objective of this calculation is to obtain an estimate of the total forming power, and thus define the set of equipments necessary for the essay. This development requires obtaining the forming process geometry. Figs. (2) and (3) show the forming geometry for the system.

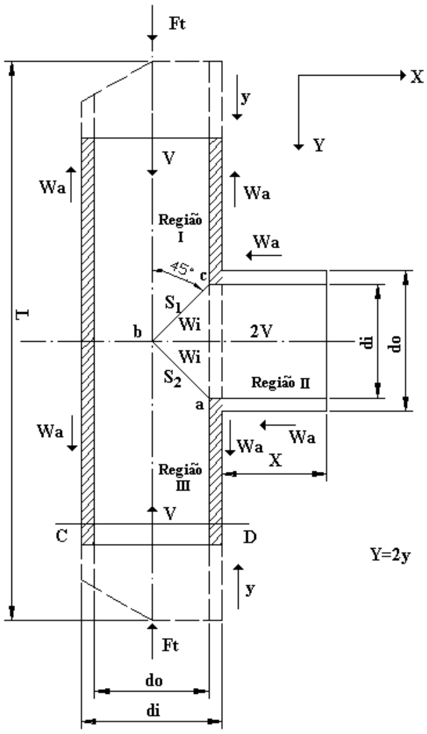

Figure. 2 – Velocity Field Strain mode

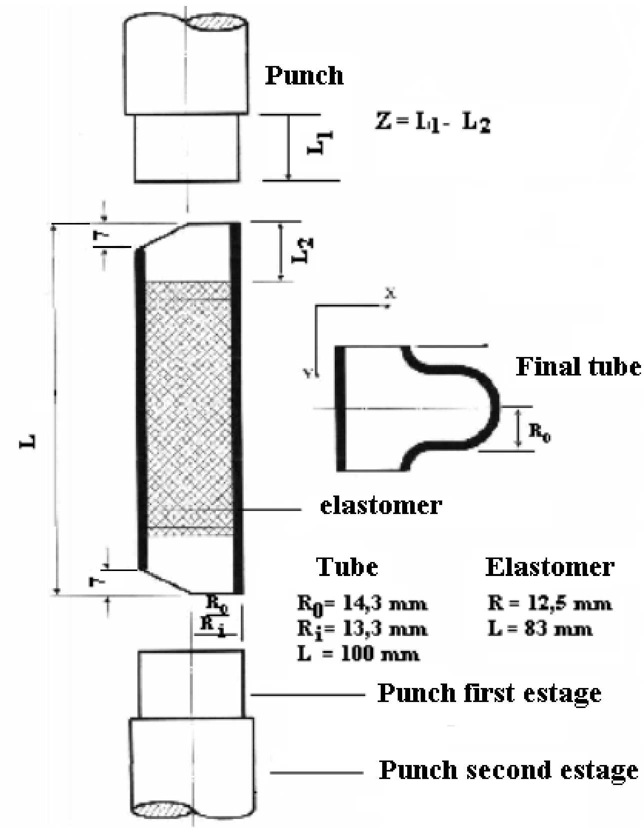

Figure. 3 – Geometric Parameters

The total power required will be determined by process energy balance, where the mass is composed by the following parts:

$$\dot{W}_e = \dot{W}_i + \dot{W}_a + \dot{W}_b \quad , \tag{1}$$

3.1. Energy due to Internal Strain ($\dot{W}_i$):

In the strain region the material suffers shear stress due to the change in the flow velocity direction. Internal strain will occur only on the S_1 and S_2 surfaces, Fig. (2), and its energy is defined as:

$$\dot{W}i = \int_S \overset{*}{V}.\tau.ds, \tag{2}$$

Solving Eq. (2), the energy due to internal strain, taking into account the anisotropy (R), is given by:

$$\dot{W}i = \frac{1}{2}.\pi.V.\sqrt{\frac{(R+1)}{(4R+2)}}.\bar{\sigma}.(do^2 - di^2), \tag{3}$$

3.2. Energy due to Friction Losses ($\dot{W}_a$):

The contribution from friction losses is given by:

$$\dot{W}a = \int_S \overset{*}{V}.\tau.ds, \tag{4}$$

where the *ds* integral is the total area between the matrix and the tube.

Assuming that the shear stress is constant and lower than the material flow shear stress one has:

$$\tau = m.\tau_o = m.\sqrt{\frac{(R+1)}{(4R+2)}}.\bar{\sigma}, \quad 0 \le m \le 1 \tag{5}$$

where *m* is the friction factor, assumed constant.

Solving Eq. (4) and using Eq. (5), the energy due to friction losses is:

$$\dot{W}a = \pi.m.V.do.L.\sqrt{\frac{(R+1)}{4R+2)}}.\bar{\sigma}, \tag{6}$$

3.3. Energy Applied to the Elastomer ($\dot{W}_b$):

The energy resulting from the elastomer compression is given by:

$$\dot{W}_b = F_b.V, \tag{7}$$

where F_b is the applied force on the elastomer rod.

The total elastomer displacement, Y_T, during the forming process is given by:

$$Y_T = Y_1 + Y_2 + Y_3, \tag{8}$$

where Y_1 is the initial displacement to fill the gap, Y_2 is the displacement due to compressibility, and Y_3 is the displacement due to the forming of the dome.

So, the total force on the elastomer is:

$$F_b = F_1 + F_2 + F_3, \tag{9}$$

where F_1, F_2 and F_3 are the forces due to displacements Y_1, Y_2 and Y_3, respectively.

3.3.1. Force F1

$$F_1 = A_0.E_c.\frac{\left(d_i^2 - d_r^2\right)}{d_r^2}, \tag{10}$$

where A_0 is the elastomer initial section area, d_i is the tube internal diameter, d_r is the elastomer initial diameter, and E_c is the theoretical modulus of elasticity given by:

$$E_C = E_o\left(1 + 2S^2\right), \tag{11}$$

where E_0 is the initial modulus of elasticity in compression (experimental) and S is the shape factor.

For this initial deformation state, the shape factor will be defined as:

$$S = \frac{A_C}{A_L}, \tag{12}$$

where A_C – loaded surface area

A_L – free surface area

3.3.2. Force F_2

$$F_2 = F_T.K.E^* \quad , \tag{13}$$

where F_T is the total force, K is the volume compressibility (Bulk Modulus), and E^* is the apparent elasticity modulus.

3.3.3. Force F_3

$$F_3 = \frac{E^*.A_i.X}{L'}, \tag{14}$$

where A_i is the tube internal area, X is the dome displacement and L' is the elastomer length after filling the gap.

Substituting Eqs. (10), (13) and (14) in (9), one gets:

$$\overset{*}{W}_b = V\left|A_{0.}E_c\left(\frac{d_i^2 - d_r^2}{d_r^2}\right) + F_T.K.E^* + \frac{E^*.A_i.X}{L'}\right|, \tag{15}$$

which represents the energy applied to the elastomer.

3.3.4. Apparent Elasticity Module E^*:

$$E^* = E_0\left\{1 + 2\left[\frac{d_i^2}{2d_0\left\{\frac{d_0}{2} + r\left|1 - \sqrt{1 - \left(\frac{X_1 - X}{r}\right)^2}\right|\right\}}\right]^2\right\}, \qquad \text{for } 0 \le X \le X_1 \tag{16}$$

$$E^* = 3E_0 \text{ for } X_1 \le X \le X_2 \tag{17}$$

3.4. External Energy Applied to the System ($\dot{W}_e$):

Due to the external forces applied, the external energy can be expressed by:

$$\dot{W}_e = 2.V.F_T \,, \tag{18}$$

3.5. Total Forming Force:

Substituting Eqs. (3), (6), (16) and (19) in (1), yields:

$$F_T = \frac{\frac{\pi}{2}.\sqrt{\frac{(R+1)}{(4R+2)}}\bar{\sigma}\left\{d_0^2 - d_i^2 + 2.m.L.d_0\right\} + A_0 E_C\left(\frac{d_i^2 - d_r^2}{d_r^2} + \frac{A_i E^*.X}{L'}\right)}{2 - K.E^*}, \tag{19}$$

which is the total forming force for a specified junction (dome) length (X).

The effective stress $\left(\bar{\sigma} = C(\bar{\varepsilon} + \varepsilon_0)^n\right)$ can, therefore, be determined through the effective strain calculated using the constant volume condition,. $\bar{\varepsilon} = \sqrt{\frac{(R+1)^2}{(2R+1)}}\ln\frac{t_x}{t_i}$. Through experimental measures of the tube wall before and after the total forming (X=do), it was verified for the copper tested that the thickness has increased about 20% on the average. Assuming a linear dependence of the thickness with X up to the maximum value of 1,2 t_i for X=do, one obtain the following empirical relationship:

$$t_x = t_i\,(1+0{,}0074X) \;\; \text{mm}, \tag{20}$$

Equation (20) can be used in the effective strain equation, which in turn, was used in Eq. (19) to calculate the total forming force. The use of Eq. (20) allows for the correction of the tube wall thickness during the forming process.

4. Results and Discussion

Analyzing Eq. (19), one verifies that it depends on geometric factors, mechanical properties, operational conditions (dome advance), friction factor (*m*), and material anisotropy (R). Due to the difficulty in determining previously the friction factor (*m*) during the process, a series of theoretical curves obtained using Eq. (19), fixing *m* and varying X up to X=do (maximum forming), were built in order to find an average value for the friction comparing the theoretical and experimental values.

Examining Fig. (5), one observes that the factor *m* (friction) for copper presents low value and variation, from 0.03 to 0.04, which can be attributed to the very good surface finishing. The variation can be explained by the fact that, as the process goes on, the lubricant between the tube external wall and the matrix looses efficiency due to its elimination, increasing the metal-to-metal contact. Due to this variation, an average friction factor of 0.037 is adopted. This result is in accordance with literature results.

Through Fig. (6) the influence of anisotropy on the forming force can be analyzed. For copper, one observes that anisotropy reinforce the tube material and so, it demands a higher level of the dome forming force. The anisotropy variation causes an increase on the dome forming force, for both anisotropy values greater than one as well as lower than one.

Another observed parameter is the initial strain-hardening influence on the dome forming force and on the material anisotropy where, through Figs. (7) and (8), it was found that the anisotropy effect is more significant when there is an initial strain-hardening. It was also verified that an increase on the strain-hardening causes an increase on the required dome forming force.

As the material's initial strain-hardening increases, the role of anisotropy is controversial, where for anisotropy values greater than one, Fig. (7), a lower force is required for the dome forming in relation to the isotropic case. On the other hand, for anisotropy values lower than one, Fig. (8), one observes an opposed behavior. However, for anisotropy values greater than one Fig. (7), or lower than one Fig. (8), for an annealing material, without initial strain-hardening, there were agreement between both cases. It can be also seen in both figures, for this special case, that the anisotropy variation causes an increase on the dome forming force as well.

Although anisotropy values greater than one reinforce the material behavior in the manufacturing process reducing the degree of thinning that the dome can experience in several points on a manufactured junction demanding higher press powers, an initial strain-hardening condition must be avoided since initial strain-hardening is harmful, due to reduce significantly the dome deforming capability.

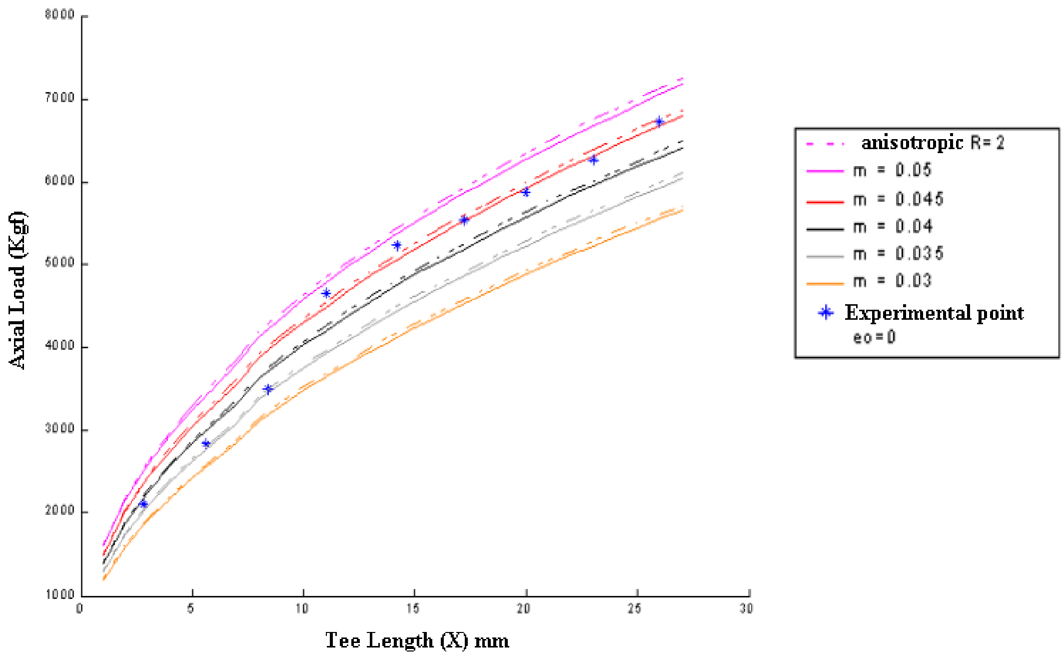

Figure 5. Theoretical and Experimental Forming Load Values - Copper.

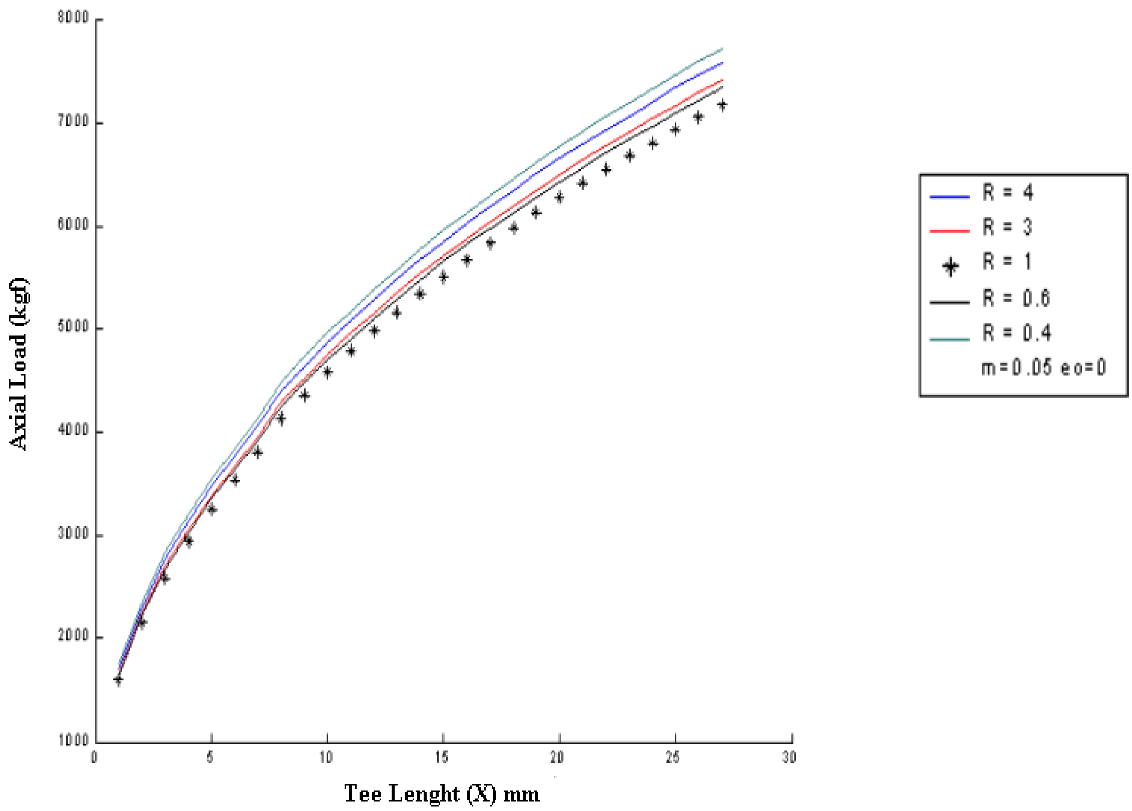

Figure 6. Anisotropy Variation - Copper.

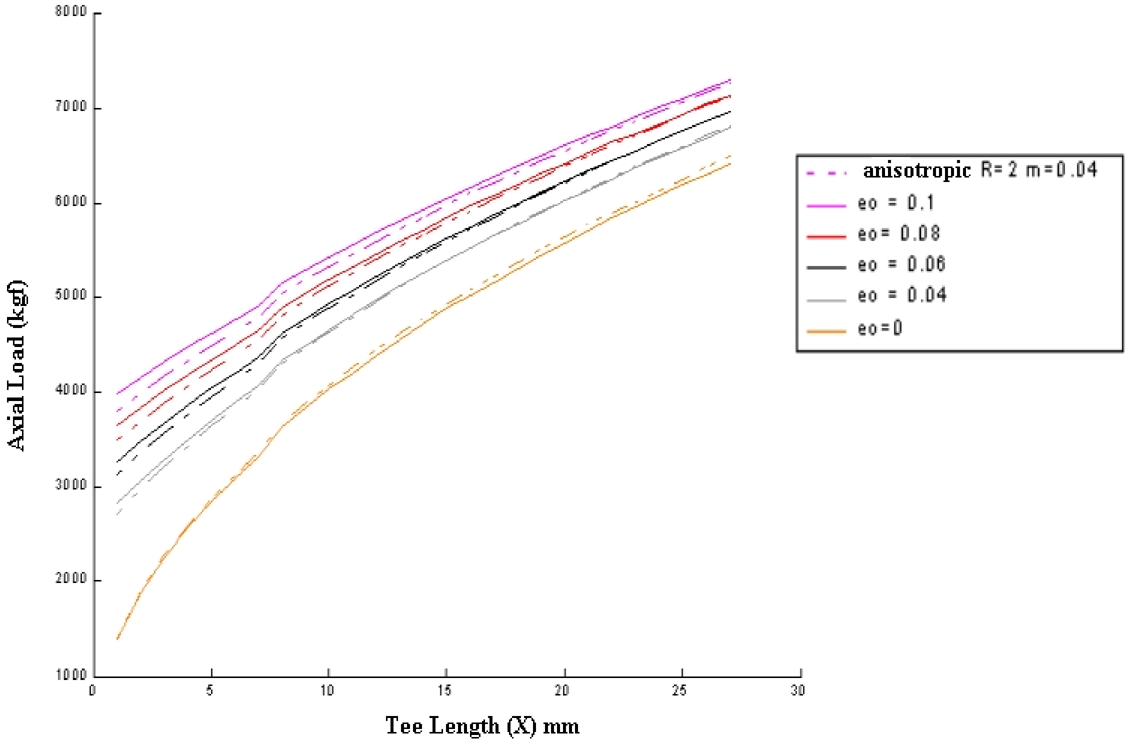

Figure 7. Tube Initial hardening variation – Anisotropy greater than one.

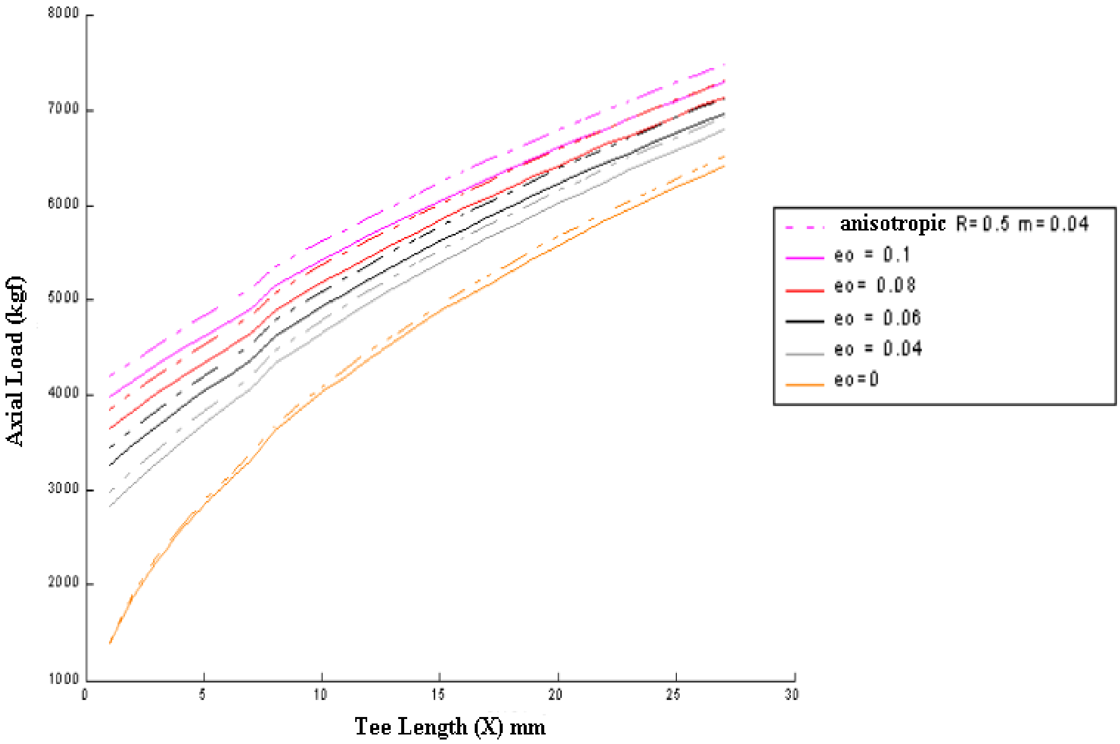

Figure 8. Tube Initial hardening variation – Anisotropy lower than one.

5. Conclusion

From the obtained results one can conclude that the proposed model is satisfactory, constituting an estimative method of the forming load calculation, useful for defining the required tools and devices.

Due to the difficulty in previously determining the friction factor (m), one can use an average value based on the obtained results, which for copper is 0.04, as a first estimate for the forming force.

One can also conclude that, although anisotropy and initial strain-hardening influence the dome forming process, one should work on the anneled material condition, eliminating the material's initial strain-hardening, mainly for the cases where anisotropy is taking into account. The theoretical role of anisotropy and initial strain-hardening on the dome forming force remain controversial yet and it needs more understanding.

In the present stage, the process represents an important elastomer application area which, due to its simplicity and tools low cost, can be an interesting option for small scale industrial production, substituting with advantages junctions obtained through conventional methods, since it is a cold forming process, increasing material resistance properties.

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