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Influence of the relative deformation rate on tube processing by ultrasonic vibration drawing(•)

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Abstract

After a brief review of the "friction reversion mechanism" during ultrasonic vibration drawing of tubes (UVD), the paper introduces a method to determine the drawing force based on the theorem of total consumed power, in the case of tube processing. The experiments performed on tubes made from 10TiNiCr180 (AISI321) austenitic stainless steel confirm the superiority of UVD technology regarding the diminution of the drawing force, the increase of the plasticity and the improvement of the safety coefficient, tendencies that are enhanced with the decrease of the relative drawing rate. The best results were obtained for the relative drawing rate of 0.12 for which the drawing force decreased with 33 %, plasticity increased with 9 % and safety coefficient with 22 %, as compared to CT.

Keywords

Ultrasonic vibration drawing. Friction reversion mechanism. Relative drawing rate. Drawing force. Tube. Kinematic characteristics. Mechanical tests. Plasticity. Safety coefficient.

La influencia de la velocidad relativa de deformación en la elaboración de tubos, al estirado por vibraciones ultrasonoras

Resumen

Después de un breve resumen del mecanismo de reversión de la fricción al estirado por vibraciones ultrasonoras (EVU), el trabajo propone un método para calcular la fuerza de estirado en base al teorema de la potencia total consumida, en el caso particular de la elaboración de tubos. Los experimentos realizados con tubos de acero inoxidable austenítico 10TiNiCr180 (AISI321) demuestran la superioridad de la tecnología EVU sobre la tecnología clásica (TC), en lo concerniente a la reducción de la fuerza de estirado, el incremento de la plasticidad y la mejora del coeficiente de seguridad, tendencias que se acentúan al diminuirse la velocidad relativa de estirado. Los mejores resultados se han obtenido en el caso de la velocidad relativa de 0,12, para la cual la fuerza de estirado se redujo, aproximadamente, un 33 %; la plasticidad se incrementó en el 9 %; y el coeficiente de seguridad aumentó un 22 % frente a la TC.

Palabras clave

Estirado por vibraciones ultrasonoras. Mecanismo de reversión de la fricción. Velocidad relativa de estirado. Fuerza de estirado. Tubo. Características cinemáticas. Ensayos mecánicos. Plasticidad. Coeficiente de seguridad.

1. INTRODUCTION

Tube mechanical working by free drawing is usually performed at room temperature where work hardening normally occurs causing the increase of mechanical resistance characteristics and the decrease of the plasticity. When less deformable metallic materials are processed according to the classical technology (CT), these phenomena are intensified in such a way that the drawing progress becomes unsafe and uneconomic mostly due to the marked augmentations of deformation force and consumed power, respectively. These two technologic parameters are directly connected to the resistance developed by metal during the plastic deformation process, which increases with

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the work hardening degree and essentially depends on three factors: (i) the cross-section reduction degree, (ii) the semiangle of the die's cone and (ii) the friction force in the metal-tool contact area[1].

One of the methods to diminish the last of the above factors, at tube processing, is the use of dies, ultrasonically vibrated on drawing direction, and located in the oscillation maxima of the waves, according to the ultrasonic vibration drawing (UVD) technology. As compared to CT, relative decreases above 30 % of the friction coefficient were obtained, when applying UVD technology at ball-bearing steel wires. These decreases were ascribed to the "reversion mechanism of the average friction force" which becomes effective if the relative drawing rate ($v_{tr}/\overline{v}_v$) is under unit[2].

The relative drawing rate defined as the ratio between drawing rate, v_{tr} and maximum vibratory rate, $\overline{v}_v$- is the key factor in UVD technology since v_{tr} determines technological productivity and $\overline{v}_v$ gives information about the device used for generation and transfer of ultrasonic energy into the deformation focus area.

The present paper presents both a theoretical and an experimental approach of austenitic stainless steel tube processing by UVD technology, aiming on one hand to derive an analytical relationship for the drawing force and on the other hand to compare theoretical and experimental results emphasizing the influence of the relative drawing rate, $v_{tr}/\overline{v}_v$.

2. THEORETICAL CONSIDERATIONS

2.1. Particularities of tube processing by UVD technology

The principle scheme of the metal-forming area at tube processing by UVD technology is introduced in figure 1. The illustrated symbols designate: D_0 – external diameter of rough tube; D – external diameter of processed tube; α – semiangle of the die's cone; τ – shear stress; σ_n – normal stress; and F^{UVD} – drawing force at UVD technology. In accordance with figure 1, any point P, arbitrarily chosen on the metal-tool interface, performs an oscillation motion with the maximum vibratory rate of the die v_v and a slip motion along the cone's generator with the feed rate v_a [3].

The kinematical particularities of tube processing by UVD technology, as compared to classical technology (CT), are schematized in figure 2. The resulting vector of the relative rate,

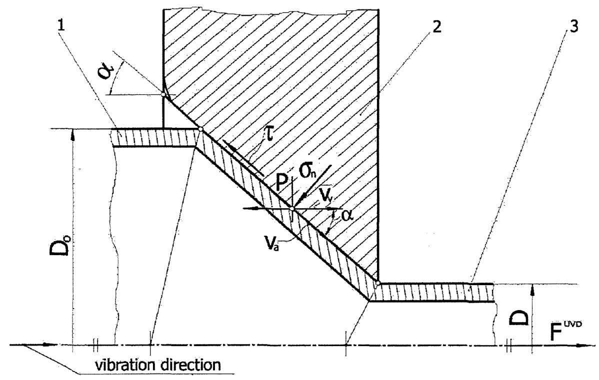

Figure 1. Principle scheme of the metal-forming area at tube processing by UVD technology: (1) rough tube; (2) die; (3) processed tube.

Figura 1. Esquema de principio del área de deformación del metal durante la elaboración de tubos mediante la tecnología EVU: (1) tubo bruto; (2) trefiladora; (3) tubo elaborado.

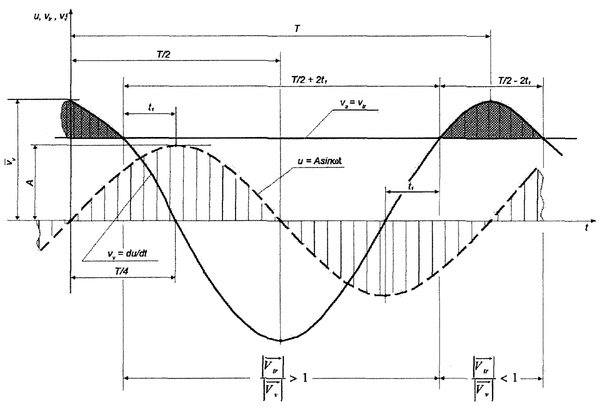

Figure 2. Kinematics elements of the plastic deformation process within UVD technology: u – displacement wave; v_{tr} – drawing rate; v_v vibration rate of the die.

Figura 2. Elementos cinemáticos del proceso de deformación plástica dentro del marco de la tecnología EVU: u- onda de desplazamento, v_{tr} – velocidad de estirado; v_v– velocidad de vibración de la trefiladora.

determined by the composition of the rates v_v and v_a, changes the displacement sense along the cone's generator of the arbitrary point P as follows: during the interval T/2 - $2t_1$ both point P and the metal move in the same sense and during T/2 + $2t_1$ they move contrarily. Assuming Coulomb-type friction at the metal-tool contact, the above model represents the ground of the "reversion mechanism of the average friction force", since the friction force becomes positive during T/2 - $2t_1$ and negative during T/2 + $2t_1$ [4].

In the case of free processing of tubes made from work hardenable metallic materials only small section reduction degrees are allowed so that die's semiangle must be α = 6 – 12°. Considering that $v_a = v_{tr} \cos \alpha$, it is a good approximation to assume $\cos \alpha \rightarrow 1$ and $v_a \cong v_{tr}$ [2 and 3]. Under these circumstances, based on relationship (11) from[4], the friction coefficient at UVD technology becomes:

$$\mu^{UVD} = \mu^{CT}\left(1 - \frac{2}{\pi}\arccos\frac{v_{tr}}{v_v}\right) \qquad (1)$$

where μ^{CT} is the friction coefficient at classical technology and $v_{tr}/\bar{v}_v \leq 1$ is the relative drawing rate, with $\bar{v}_v$ = max (du/dt) = max [dAsin(2πft)/dt] = 2πfA = die's maximum vibratory rate (A, f – amplitude and frequency of die's oscillations, respectively)[4].

Relationship (1) shows that, assuming μ^{CT} constant, the only way to reduce μ^{UVD} is to minimize the relative drawing rate, $\bar{v}_{tr}/v_v$.

2.2. Determination of the drawing force at UVD technology

The determination of the drawing force at UVD technology is based both on the theorem of total consumed power and the "reversion mechanism of the average friction force", considering the geometry and kinematics of axial-symmetrical conical movement into the deformation focus as illustrated in figure 3. The geometrical elements are: R_0, R – external radius of rough and processed tube, respectively; r_0, r – internal radius of rough and processed tube, respectively; g_0, g – wall thickness of initial and final tube, respectively; β_0 – initial cone semiangle, with rate discontinuities; and β_f – final cone semiangle, with rate discontinuities. The kinematical elements are: v_0 – initial rate of the tube; v – rate in the deformation focus; v_{tr} – drawing rate. F^{UVD} and σ^{UVD} represent the drawing force and stress, respectively. The rest of the parameters have the same meaning as above. In addition, the following assumptions are adopted: (i) the metallic material is totally incompressible; (ii) the die is a rigid body; (iii) metal deformation is performed according to Von Mises's flowing condition; (iv) the kinematical rate field provides a Bernoulli-type continuity; (v) at metal-tool interface, a Coulomb-type friction is produced that is considered constant for a given drawing process; (vi) at the oscillating system level only longitudinal elastic

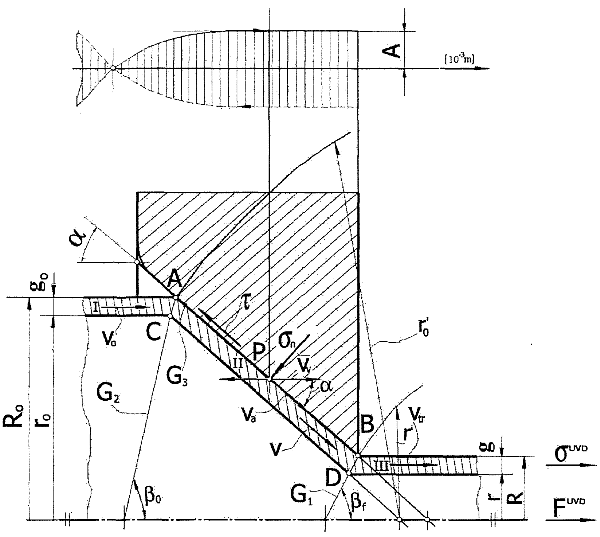

Figure 3. Geometrical and kinematical elements of the axial-symmetrical conical movement; solid line – progressive wave; dotted line – regressive wave.

Figura 3. Elementos geométricos y cinemáticos del movimiento cónico axial simétrico; línea continua – onda progresiva, línea punteada – onda regresiva.

waves are acting under stationary regime (forming nodes and venters) and (vii) the plastic deformation process is isothermal, the thermal effects of internal friction being neglected[1, 2, 5 and 6]. With the above assumptions and in accordance with figure 3, the calculation relationship for the drawing force is:

$$F^{UVD} = \pi(R^2 - r^2)\sigma^{UVD} \qquad (2)$$

For the geometry and kinematics of axial-symmetrical conical movement, schematized in figure 3, the following coefficients are introduced[3]:

$$K = \frac{g}{g_0}; K_1 = \frac{R}{R_0}; K_2 = \frac{r}{R}; K_3 = \frac{r_0}{R_0}; K_4 = \frac{1-K_2}{1-K_3}; K_5 = \frac{1+K_2}{1+K_3} \qquad (3)$$

The tube has been divided into three zones with continuous rate fields: zones I and III that have uniform axial rates since the drawing rate coincides with the tube's symmetry axis and zone II (deformation area) has the rate direction making α angle with the symmetry axis. Zone II, characterized by metal flow parallel to the die's active surface, is delimited by the conical surfaces G_1 and G_2, represented by the segments BD and AC and defined by the angles β_f and β_0, respectively and is externally limited by surface G_3. Based on experimental observations it was noticed that tube wall thickness is reduced only at the beginning of proper plastic deformation. This means that, considering the tube's geometry into the deformation area, angles β_0 and β_f can be determined with[1, 2 and 6]:

$$\beta_0 = (\pi - \alpha)/2 \qquad (4)$$

and:

$$\beta_f = \arctan\left(\frac{K\sin\alpha}{1 - K\cos\alpha}\right) = \arctan\left(\frac{K_1K_4\sin\alpha}{1 - K_1K_4\cos\alpha}\right) \qquad (5)$$

From the continuity condition of the metal flow, for rates v_0 and v_{tr} it follows that:

$$\frac{v_0}{v_{tr}} = \frac{R^2 - r^2}{R_0^2 - r_0^2} = K_1^2\frac{1 - K_2^2}{1 - K_3^2} \qquad (6)$$

At the level of the three surfaces that delimit the deformation area, rate discontinuities have the expressions:

$$\Delta v_1 = v_{tr}\frac{\sin\alpha}{\sin(\alpha + \beta_f)}, \text{ on surface } G_1 \qquad (7)$$

$$\Delta v_2 = v_0 \cdot 2\sin(a/2), \text{ on surface } G_2 \qquad (8)$$

$$\Delta v_3 = v = v_{tr}\frac{R^2 - r^2}{R_0^2 - (R_0 - g_0\cos\alpha)}\cos^2\alpha, \text{ on surface } G_3 \qquad (9)$$

During the drawing, the total consumed power must compensate the losses produced: (i) by proper plastic deformation ($\dot{W}_d$); (ii) by shear due to rate discontinuities on surfaces G_1 and G_2 ($\dot{W}_{G1,2}$) and (iii) by friction on surface G_3 ($\dot{W}_f$).

The power consumed by plastic deformation is determined with:

$$\dot{W}_d = \dot{V}\left(2/\sqrt{3}\right)\sigma_c\sqrt{(1/2)\varepsilon_{ij}\varepsilon_{ji}} \qquad (10)$$

The components ε_{ij} and ε_{ji} of the deformation tensor, in cylindrical coordinates, have the expressions:

$$\varepsilon_{PP} = \ln\frac{R - r}{R_0 - r_0} = \ln(K_1K_4) \qquad (11)$$

$$\varepsilon_{\theta\theta} = \ln\frac{R + r}{R_0 + r_0} = \ln(K_1K_5) \qquad (12)$$

$$\varepsilon_{ZZ} = -(\varepsilon_{RR} + \varepsilon_{\theta\theta}) \qquad (13)$$

$$\varepsilon_{R\theta} = \varepsilon_{RZ} = \varepsilon_{\theta Z} = 0 \qquad (14)$$

In the above, σ_c is the yield stress of the deformed metal and $\dot{V}$ the volume rate:

$$\dot{V} = \pi v_{tr}(R^2 - r^2) \qquad (15)$$

Consequently, the power consumption due to plastic deformation becomes:

$$W_d = \left(2/\sqrt{3}\right)\sigma_c\pi v_{tr}R^2\left[1 - (r/R)^2\right]\sqrt{\varepsilon_{RR}^2 + \varepsilon_{\theta\theta}^2 + \varepsilon_{RR}\varepsilon_{\theta\theta}} \qquad (16)$$

The power consumed during surface G_1 crossing is:

$$W_{G_1} = \int_{SG_1} \tau\Delta v_1 ds \qquad (17)$$

where shear stress is $\tau = \left(1/\sqrt{3}\right)\sigma_c$, Δv_1 is given by relationship (7) and SG_1 is G_1 surface area given by:

$$SG_1 = \pi(R^2 - r^2)/\sin\beta_f \qquad (18)$$

Therefore, the power consumed during surface G_1 crossing becomes:

$$\dot{W}_{G_1} = \left(1/\sqrt{3}\right)\sigma_c\pi v_{tr}R^2\left[1 - (r/R)^2\right]\left[\sin\alpha/\sin\beta_f\ \sin(\alpha + \beta_f)\right] \qquad (19)$$

Similarly, the power consumed during surface G_2 crossing is:

$$W_{G_2} = \left(\sigma_3/\sqrt{3}\right)v_0 \cdot 2\sin(\alpha/2) \cdot \pi\left[\left(R_0^2 - r_0^2\right)/\sin\beta_0\right] = $$
$$= \left(2/\sqrt{3}\right)\sigma_c\pi v_{tr}R^2\left[1 - (r/R)^2\tan(\alpha/2)\right] \qquad (20)$$

The power consumed due to friction losses on surface G_3 is determined with:

$$\dot{W}_f = \dot{W}_{G_3} = \int_{SG_3} \tau\Delta v_3 ds \qquad (21)$$

Shear stress can be expressed as $\tau = \sigma_n \cdot \mu^{UVD}$, as a function of the normal stress σ_n and the friction coefficient at UVD technology given by relationship (1).

The elementary surface *ds* has the expression:

$$ds = \frac{2\pi}{\sin\alpha}RdR, \ R \in [R, R_0] \qquad (22)$$

The normal stress can be determined based on Sach's relationship[2]:

$$\sigma_n \cong \sigma_c \left[\ln\left(\frac{R_0}{R}\right)^2 - 1 \right] \quad (23)$$

With the above relationships, the power consumed by friction on surface G_3 becomes:

$$\dot{W}_{G_3} = \int_{SG_3} \mu^{UVD} \sigma_c \left[\ln\left(\frac{R_0}{R}\right)^2 - 1 \right] \Delta v_3 ds \quad (24)$$

therefore:

$$\dot{W}_{G_3} = \mu^{UVD}\sigma_c\left[\ln\left(\frac{R_0}{R}\right)^2 - 1\right] v_{tr}\left(R^2 - r^2\right)\frac{\cos\alpha}{g_0}\cdot\frac{\pi}{\sin\alpha}\int_R^{R_0}\frac{RdR}{R - \frac{g_0}{2}\cos\alpha} = \quad (25)$$
$$= \mu^{UVD}\sigma_c\left[\ln\left(\frac{R_0}{R}\right)^2 - 1\right] v_{tr}\left(R^2 - r^2\right)\frac{\pi\cos\alpha}{g_0\sin\alpha}\left[R - \frac{g_0}{2}\cos\alpha\cdot\ln\left(R - \frac{g_0}{2}\cos\alpha\right)\right] =$$
$$= \frac{\pi\mu^{UVD}\sigma_c}{g_0} v_{tr}\left(R^2 - r^2\right)\left[\ln\left(\frac{R_0}{R}\right)^2 - 1\right]\frac{\cos\alpha}{\sin\alpha}\left[(R_0 - R) - \frac{g_0}{2}\cos\alpha\cdot\ln\frac{R_0 - \frac{1}{g_0}\cos\alpha}{R_0 - \frac{1}{2}g\cos\alpha}\right]$$
$$= \pi\mu^{UVD}\sigma_c v_{tr} R^2(1 - K_2^2)Q_2$$

where:

$$Q_2 = \left(\ln K_1^{-2} - 1\right)\left[\frac{1 - K_1}{1 - K_3} + \frac{\cos\alpha}{2}\ln\frac{2 - (1 - K_3)\cos\alpha}{2K_1 - (1 - K_3)\cos\alpha}\right]\cot\alpha \quad (26)$$

From the balance of the total consumed power at UVD technology it follows that the drawing stress has the expression:

$$\sigma^{UVD} = \frac{2\sigma_c}{\sqrt{3}} Q_1 + \sigma_c \mu^{UVD} Q_2 \quad (27)$$

where:

$$Q_1 = \sqrt{\varepsilon_{RR}^2 + \varepsilon_{\theta\theta}^2 + \varepsilon_{RR}\varepsilon_{\theta\theta}} + \frac{\sin\alpha}{2\sin\beta_f \sin(\alpha + \beta_f)} + \tan\frac{\alpha}{2} \quad (28)$$

With relationship (27) introduced in (2) the drawing force becomes:

$$F^{UVD} = \pi(R^2 - r^2)\left(\frac{2\sigma_c}{\sqrt{3}} Q_1 + \sigma_c \mu^{UVD} Q_2\right) \quad (29)$$

In the case of classical technology (CT) the drawing stress can be determined considering relationship (27):

$$\sigma^{CT} = \frac{2\sigma_c}{\sqrt{3}} Q_1 + \frac{2\sigma_c}{\pi} \mu^{CT} Q_2 \quad (30)$$

This allows determining the drawing force as:

$$F^{CT} = \pi(R^2 - r^2)\sigma^{CT} \quad (31)$$

The magnitude of the drawing stress must not exceed the tensile strength, even with the increment caused by work hardening. This condition can be expressed by means of the safety coefficient of drawing[2 and 6]:

$$C = \frac{S\sigma_r}{F} \quad (32)$$

where σ_r is the tensile strength, S is the cross-section surface (at the end of deformation zone) and F the drawing force (F^{CT} or F^{UVD}).

As compared to CT, the effectiveness of UVD technology as a function of the magnitude of drawing force can be expressed by the relative force reduction[4]:

$$AF = \frac{F^{CT} - F^{UVD}}{F^{CT}} \cdot 100 \quad (33)$$

3. EXPERIMENTAL PROCEDURE

The principle scheme of the experimental installation, used for tube processing according to UVD technology[4], is illustrated in figure 4. The ultrasonic generator, type U.Z.G. 2-4M, has a power of 2000 W and works at a resonance frequency f = $17.5\cdot10^3$ Hz in conjunction with the oscillating system, type P.M.S. 15A-18. The construction and functioning of the oscillating system are illustrated in figure 5. After being

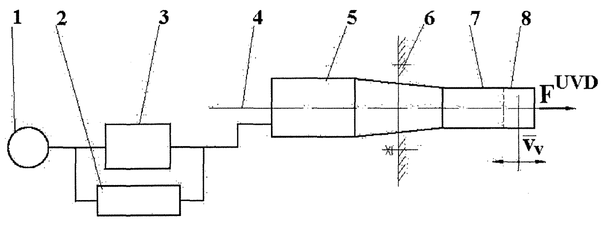

Figure 4. Principle scheme of the experimental installation used for tube processing by UVD technology: (1) electrical supplying bloc; (2) polarization bloc; (3) ultrasonic generator, type U.Z.G. 2-4M; (4) rough tube; (5) oscillating system, type P.M.S. 15A-18, with nodal flange; (6) resistance frame of classical drawing equipment; (7) guide for ultrasonic waves; (8) die.

Figura 4. Esquema de principio de la instalación utilizada para la elaboración de tubos por la tecnología EVU: (1) bloque de alimentación eléctrica, (2) bloque de polarización, (3) generador de ultrasonidos, tipo U.Z.G. 2-4M; (4) tubo bruto, (5) sistema oscilante, tipo P.M.S. 15A-18, con brida nodal, (6) marco de resistencia del equipo clásico de estirado, (7) guía para ondas ultrasonoras, (8) trefiladora.

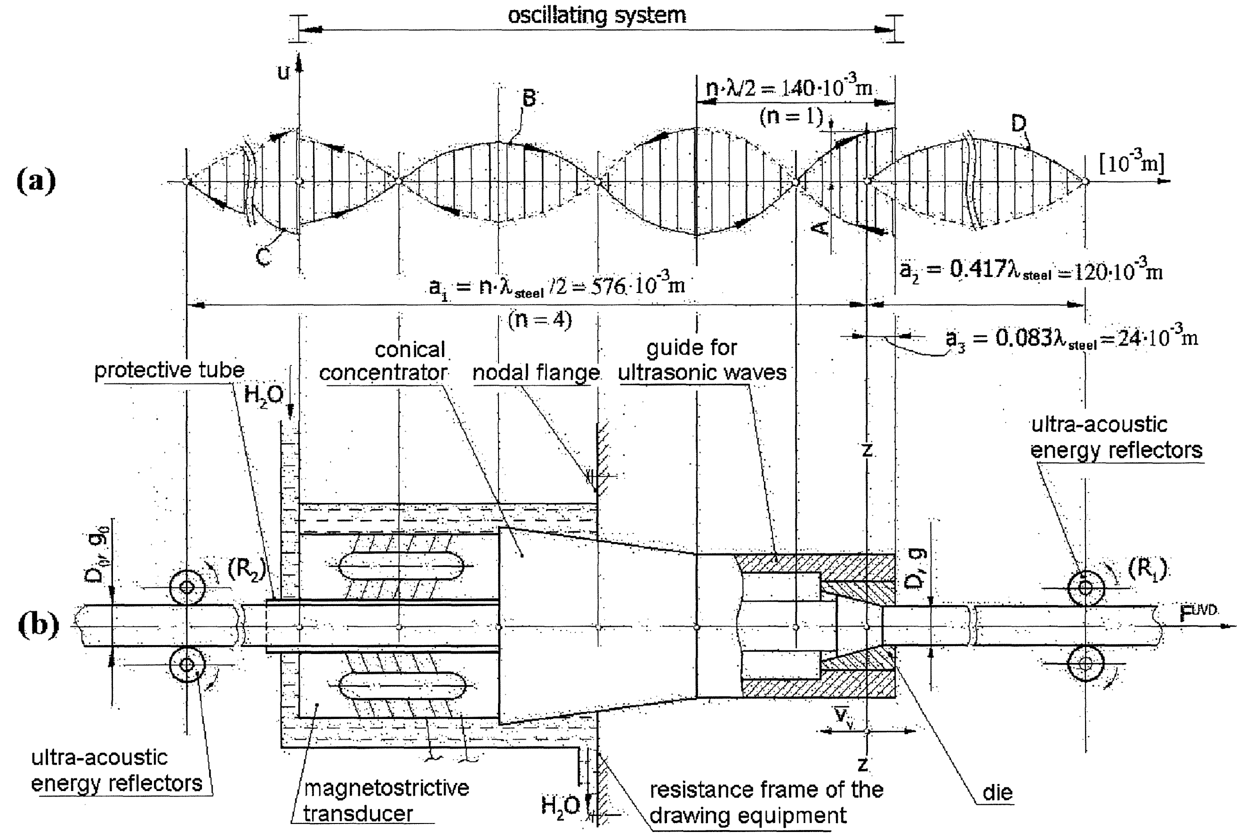

Figure 5. Functional and constructive details of the oscillating system: (a) waves oscillation along the oscillating system (B) in the rough tube (C) and in the processed tube (D); (b) constructive scheme of the proper oscillating system.

Figura 5. Detalles constructivos y funcionales del sistema oscilante: (a) oscilación de las ondas a través del sistema oscilante (B) en el tubo bruto (C) y en el tubo elaborado (D); (b) esquema constructivo del sistema oscilante propiamente dicho.

generated by the magnetostrictive transducer, the ultrasonic waves are first amplified by the conical concentrator and then directed by the guiding device towards the tungsten carbide die, which is hot pressed at one of its ends. In figure 5a, λ represents the ultrasonics wavelength in the titanium alloy of the guide for ultrasonic waves, determined as 0.28 m [4], λ_{steel} is the wavelength of ultrasonics in the steel tube, determined as 0.288·m[3] and n is the integer number of nodes. Since the guide for ultrasonic waves comprises one node, its length is a half of the corresponding wavelength, 0.14·m. In order to focus the action of ultrasonic energy upon well defined lengths both in rough and processed tube, ultra-acoustic energy reflectors are used, represented in figure 5b by the pressure rolls R_1 and R_2. Reflector R_1 is located at the distance a_2 = 0.12 m from the vertical line *z-z* and reflector R_2 at the distance a_1 = 0.576 m. For a good efficiency of plastic deformation by UVD technology, it is recommended that the vertical line *z-z* to be located at the distance a_3 = 0.024 m from the frontal surface of the guide for ultrasonic waves[7]. During the experiments a classical hydraulically actuated drawing bench was used able to develop a drawing force of $12\cdot10^4$ N and an active stroke of 1.5 m. The oscillating system has been fastened on the resistance frame of the classical drawing equipment by means of the nodal flange.

The experiments were performed on tube samples of 10TiNiCr180 (AISI321) austenitic stainless steel provided by the Romanian company S.C.OMEGATUB S.A.Iaşi at the initial dimensions $D_0 = 4.85\cdot10^{-3}$m, $g_0 = 0.7\cdot10^{-3}$ m and 1.2 m length. The tube coil was solution treated in a 98 % $BaCO_3$ salt bath (preheating at 873 K, holding 1313 K/ 300 s and water-quenching) and tempered (623 K/300 s/ air) for stress relieving. The chemical composition of rough tubes was: Fe- 0.1 C- 2.0 Mn- 1.0 Si- 0.03 S- 0.045 P- 18.5 Cr- 9 Ni- 0.7 Ti (wt. %).

The experiments aimed to reveal the influence of the relative drawing rate on the drawing force, the mechanical characteristics and the safety coefficient of drawing. In this purpose, the cross-section reduction degree, r = 18 % and the semiangle of the die's cone, α = 8°, were kept constant while the friction force in the metal-tool contact area was varied by means of the friction coefficient at UVD technology, μ^{UVD} [4, 8, 9 and 10]. In order to vary the relative rate, drawing rate was kept constant, v_{tr} = 0.33 m/s, and maximum vibratory rate was modified by step tuning the amplitude (A = 5; 10; 15; 20 and 25·10^{-6}m) by controlling both the supply voltage of the transducer and the premagnetization current. In this way, 5 different maximum vibratory rates were obtained ($\overline{v}_v$= 0.55; 1.09; 1.65; 2.2 and 2.74 m/s), which give 5 different relative drawing rates, $v_{tr}/\overline{v}_v$ = 0.6; 0.3; 0.2; 0.15 and 0.12, respectively. Increasing $\overline{v}_v$ above 2.74 m/s was not possible at laboratory level since amplitudes larger than 25·10^{-6}m would require geometrical changes of the guide for ultrasonic waves. For each relative rate 5 different specimens were processed the corresponding average results being designated as A, B, C, D and E, respectively. The tube samples were processed by single stage drawing, both by UVD technology and CT, the final dimensions of the processed tube being: D = 4.32·10^{-3}m and g = 0.65·10^{-3}m. As lubricant, 45 % chlorided paraffin was used. The rest of the technological and experimental details were given in the bibliography[4].

For the determination of the mechanical characteristics of the resistance (yield stress, $R_{p0.2}$, and tensile strength, R_m) and plasticity (ultimate strain, A_5), tensile tests were performed, according to EN 10002-1/1995, with a strain rate of 3.33·10^{-4} m/s, on a MTS 810.24 tensile testing machine. In the initial state, the tube samples had the following mechanical characteristics: $R_{p0.2}$ (σ_c)= 320 MPa, R_m = 486 MPa and A_5 = 38 %.

4. EXPERIMENTAL RESULTS AND DISCUSSION

In the case of CT the drawing force, determined as an average of 5 tests, was F_{ex}^{CT} = 812 N. With this value, by means of relationship (31), the drawing stress for CT was calculated as σ^{CT} = 109 MPa. The friction coefficient for classical technology, μ^{CT} = 0.026, was determined with relationship (30) and the relative drawing stress was: σ^{CT}/σ_c = 0.3. On tensile specimens processed by CT, due to work hardening, the yield stress and the tensile strength increased ($R_{p0.2}$ = 352 MPa and R_m = 532 MPa) and the ultimate strain decreased (A_5 = 32.2 %) as compared to the initial state. The safety coefficient of drawing by CT was determined with relationship (32) as C^{CT} = 4.89.

The technological parameters, the safety coefficient of drawing and the mechanical characteristics of the specimens processed by UVD technology are listed in table I. Each experimental value represents the average of 5 tests. The values of drawing stress, drawing force and friction coefficient were determined both analytically (μ_{an}^{UVD}, σ_{an}^{UVD} and F_{an}^{UVD}) and experimentally (μ_{ex}^{UVD}, σ_{ex}^{UVD} and F_{ex}^{UVD}). Analytical friction coefficients at UVD technology, μ_{an}^{CT}, were derived as a function of relative drawing rates $v_{tr}/\overline{v}_v$, by means of the friction coefficient for classical technology, μ^{CT}, using relationship (1). The

Table I. Technological parameters, safety coefficient of drawing and mechanical characteristics at 10TiNiCr180 (AISI 321) austenitic stainless steel tube processing according to UVD technology

Tabla I. Parámetros tecnológicos, coeficiente de seguridad de estirad y características mecánicas en la elaboración de tubos de acero inoxidable austenítico 10TiNiCr180 (AISI 321) por la tecnología EVU

Spe-cimen set	Technological parameters								Safety coefficient	Mechanical characteristics		
	$\frac{V_{tr}}{V_v}$	F_{an}^{UVD}	F_{ex}^{UVD}	σ_{an}^{UVD}	σ_{ex}^{UVD}	μ_{an}^{UVD}	μ_{ex}^{UVD}	$\frac{\sigma_{ex}^{UVD}}{\sigma_c}$	C^{UVD}	$R_{p0.2}^{UVD}$	R_m^{UVD}	A_5^{UVD}
		N	N	MPa	MPa	10-3	10-3	-	-	MPa	MPa	%
A	0.6	705	676	94	91	6.2	6.7	0.26	5.62	349	509	33.2
B	0.3	668	637	89	85	5.2	5.6	0.244	5.83	348	498	33.6
C	0.2	638	597	85	80	4.4	4.8	0.233	6.10	343	488	34.0
D	0.15	633	574	83	77	3.0	3.5	0.229	6.22	335	478	34.5
E	0.12	600	545	80	73	2.0	2.4	0.222	6.29	328	459	35.4

analytical drawing stresses σ_{an}^{UVD} were calculated with relationship (27) and analytical drawing forces, F_{an}^{UVD} with relationship (29). It is noticeable that for each of the specimen sets, $F_{an}^{UVD} > F_{ex}^{UVD}$. The higher analytical values could be caused, besides the formerly mentioned intermittent metal forming and lubricant's effectiveness increase[4], by the softening effect of ultrasonics occurring in the 4 nodes of the waves oscillation in the rough tube, (Fig. 5a). σ_{ex}^{UVD} were determined based on the experimental drawing forces by means of relationship (2). The experimental values of the friction coefficient at UVD technology, μ_{ex}^{UVD} were calculated with relationship (27) as a function of σ_{ex}^{UVD}.

From table I it is noticeable that, in the case of UVD technology, the drawing force decreased with the decrease of relative drawing rate. The variation tendencies of the drawing force and the UVD effectiveness with the relative drawing rate are illustrated in figure 6. As compared to CT, the maximum relative reduction of drawing force (UVD effectiveness) has exceeded 32 % corresponding to the relative drawing rate of 0.12. The drawing force reduction has been ascribed to the "reversion mechanism of average friction force", which is the main responsible for the diminution of experimental friction coefficients, μ_{ex}^{UVD}. Another consequence of this diminution is the decrease of the relative drawing stresses ($\sigma_{ex}^{UVD}/\sigma_c$) which reflects the intensity weakening of work hardening process.

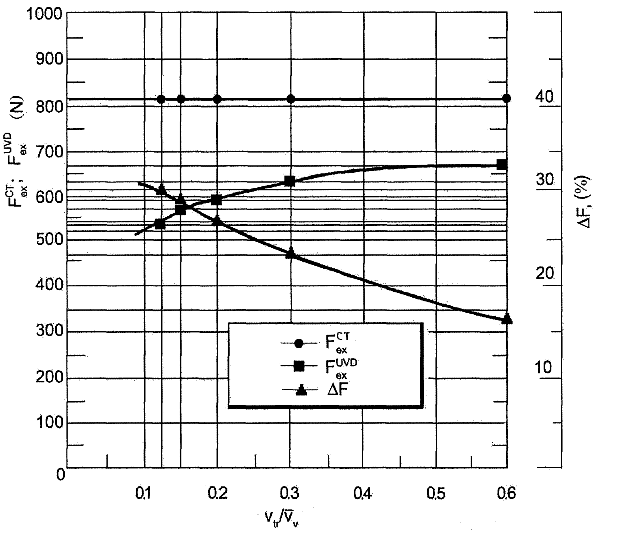

Figure 6. Influence of the relative drawing rate ($v_{tr}/\bar{v}_v$) on the experimental drawing force (F_{ex}^{UVD}) and the efficiency (ΔF) of UVD technology as compared to classical technology (F_{ex}^{CT}= ct.), at 10TiNiCr180 (AISI 321) austenitic stainless steel tube processing.

Figura 6. La influencia de la velocidad relativa de estirado ($v_{tr}/\bar{v}_v$) sobre la fuerza de estirado experimental (F_{ex}^{UVD}) y sobre la eficacia de la tecnología EVU (ΔF) frente a la tecnología clásica (F_{ex}^{CT}= ct.) en la elaboración de tubos de acero inoxidable austenítico 10TiNiCr180 (AISI 321).

This decrease of intensity of the work hardening phenomenon in ultrasonically drawn steel tubes, as compared to CT, causes on one hand the obtainment of lower characteristics of mechanical resistance and higher plasticity and on the other hand the increase of safety coefficient of drawing. Thus, for each of the 5 values of $v_{tr}/\bar{v}_v$ it is obvious that:

$$R_{p0.2}^{CT} > R_{p0.2}^{UVD}, R_m^{CT} > R_m^{UVD}, A_5^{CT} < A_5^{UVD} \text{ and } C^{CT} < C^{UVD}.$$

In order to emphasize these variations, caused by UVD technology, the relative decreases as compared to CT were determined with:

$$\Delta R_{p0.2} = \frac{R_{p0.2}^{CT} - R_{p0.2}^{UVD}}{R_{p0.2}^{CT}} \cdot 100 \text{ and} \qquad (34)$$

$$\Delta R_m = \frac{R_m^{CT} - R_m^{UVD}}{R_m^{CT}} \cdot 100$$

while the relative increases with:

$$\Delta A_5 = \frac{A_5^{UVD} - A_5^{CT}}{A_5^{UVD}} \cdot 100 \text{ and} \qquad (35)$$

$$\Delta C = \frac{C^{UVD} - C^{CT}}{C^{UVD}} \cdot 100$$

In this case, as well, the maximum relative decreases were obtained for $v_{tr}/\bar{v}_v$=0.12, namely: $\Delta R_{p0.2}$ = 6.81 %, ΔR_m = 13.72 %, ΔA_5 = 9.03 % and ΔC = 22.25 %. The influence of $v_{tr}/\bar{v}_v$ on the relative variations of the yield stress, tensile strength, ultimate strain and the safety coefficient of drawing is illustrated in figure 7.

5. CONCLUSIONS

A series of analytical contributions and experimental evidence to the previously explained "reversion mechanism of the average friction force"[4] were introduced in the particular case of 10TiNiCr180 (AISI321) austenitic stainless steel tube processing using conical convergent dies, ultrasonically vibrated on drawing direction, and located in the oscillation maxima of the waves. Based on the theorem of total consumed power, a calculation method has been proposed for the

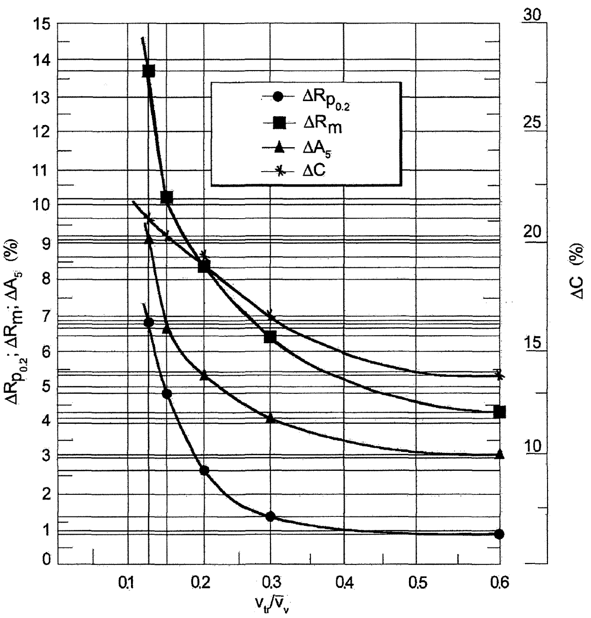

Figure 7. Variation of the relative reductions of the yield stress ($\Delta R_{p0.2}$), tensile strength (ΔR_m) and the ultimate strain (ΔA_5) and relative increase of the safety coefficient of drawing (ΔC) as a function of the drawing rate ($v_{tr}/\bar{v}_v$)) at 10TiNiCr180 (AISI 321) austenitic stainless steel tube processing.

Figura 7. Variaciones relativas de la reducción de la resistencia a la corriente ($\Delta R_{p0.2}$) y la resistencia a la rotura (ΔR_m), y del incremento de la elongación a la rotura (ΔA_5) y del coeficiente de seguridad de estirado (ΔC), en función de la velocidad relativa en la elaboración ($v_{tr}/\bar{v}_v$) de tubos de acero inoxidable austenítico 10TiNiCr180 (AISI 321).

drawing force and a good agreement was obtained between theoretical and experimental values. The experiments proved that, the lower the relative drawing rate the lower the drawing force, the higher the drawn materials plasticity and the safety coefficient of drawing. The reported results prove that UVD technology is recommended in the case of processing work hardenable materials, which request the use of reduced drawing rates corresponding to low values of the v_{tr}/v_v ratio.

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