Influence of the ultrasounds surface effect at the ultrasonic drawing of the thin walls tubes made of stainless steel

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The paper presents the influence of the ultrasounds surface effect up the drawing force and up the mechanical characteristics of resistance and plasticity, at the processing of the thin walls tubes made of X5CrNi18-10 / EN 1008-3 / 2005, in ultrasound field / UVD system. The drawing force is measured with the drawing cell, a CT-A-KN1C one, (during the process of plastic deformation by drawing) and the mechanical characteristics of resistance and plasticity are determined by tension stress on samples made of classic processed tube (CT) and of ultrasonic processed tube (UVD) – accordingly with EN 10002-2-1995. The ultrasounds surface effect or the effect of the metal-tool contact friction reduction / Severdenko's model, is explained based on the mechanism of the mean friction reversal at the level of one complete time of the oscillation (T), assuming a Coulomb type friction. As a reduction measure of the friction at the metal-tool contact is the reduction coefficient of the mean friction (φ) – as a function of the relative rate of drawing ($v_{dr}/\bar{v}_v$), where v_{dr} is the rate of drawing and $\bar{v}_v$ is the vibratory rate of the die. The results important to be considered are for $v_{dr}/\bar{v}_v$ << 1.0

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1. Introduction

The counted on effect of the ultrasonic energy in the plastic deformation processes by drawing in ultrasound field is obtained when there are used high energy ultrasounds – longitudinal ultrasonic waves as standing waves which generate vertexes and antinodes / minimum and maximum positions of the wave oscillations, [1, 2, 3, 4, 5]. As a fact, depending on the placement of the deformation focus, it is obtained the softening effect / the volume effect or the effect of the metal-tool contact friction reduction / the ultrasounds surface effect (it takes place at the metal-tool interface), [2, 4, 5].

The softening effect or the volume effect is obtained when the tool used for the deformation / the die is placed in the vertex / minimum position of the wave oscillations.

The ultrasounds surface effect is obtained when the die is placed in the maximum position / the antinode of the wave oscillations and it is activated along the drawing direction, "the ultrasonic vibration drawing – UVD" / UVD system, [2, 4, 5].

The ultrasounds are a sort of elastic waves which have the values of frequency between 16.000 and 10^{10} Hz. The area of the elastic medium which is in a vibratory state and which is the placement of the ultrasonic waves is called the ultrasound field.

The softening effect or the volume effect can be applied when the measures of the static stresses used for the deformation are comparable with the measures of the dynamic / ultrasonic once – induced in the focus of the deformation. This is the case of the processing by drawing of the high plasticity metallic materials.

The ultrasounds surface effect / the metal-tool contact friction reduction is very important in the case of the metallic materials which have low plasticity and which are capable of being strong hardened by cold plastic deformation; it is intensive studied in comparison with the softening effect / the volume effect, [2, 4, 6].

The volume effect is explained based on the overlapping of the stresses and the ultrasounds surface effect is explained based on the mechanism of the mean friction reduction, [1, 2, 4, 5].

Making a comparison, the stainless steels have much bigger values for the cold plastic deformation resistance and for the intensity of the hardening then the carbon steels, [2, 4].

The paper presents the influence of the ultrasounds surface effect during the processing of the cylindrical symmetry thin walls tubes made of X5CrNi18-10 stainless steel, in ultrasound field / UVD system.

The measure of the mean friction reduction at the metal-tool contact is the value of the coefficient φ – which, for a given drawing process, depends on the relative rate of drawing, ($v_{dr}/\bar{v}_v$), the ratio between the value of the rate of drawing, (v_{dr}) and the maximum value of the ultrasonic vibratory rate of the die, ($\bar{v}_v$), [2].

The thin walls tubes, (g_i / D_i<0.16, where g_i is the wall thickness and D_i is the exterior diameter of the tube), are very appropriate for the plastic deformation by cold drawing in ultrasound field / UVD system, because, in this case, it does not take place an important damping of the ultrasounds into the mass of the metal / the wall thickness; there are created excellent conditions for the obtaining of "the ultrasounds surface effect" when $v_{dr}/\bar{v}_v$ *<<1.0,* which is usually obtained during the processing by drawing of this kind of products, [2, 4, 7, 8, 10].

The experimental researches take into account the influence of the ultrasounds surface effect to the drawing force and to the mechanical characteristics of resistance and plasticity of the tube samples processed in UVD system, making a comparison with the same in classic technology – CT.

2. Developing of the ultrasounds surface effect

The first researchers who have realized a theoretical model for the reduction of the mean friction at the metal-tool contact, assuming friction as a Coulomb type one, were Severdenko and Miskevici – in the present time, this model is known as so called "The Severdenko Model", [2, 4, 5]. The Fig. 1 presents the scheme of the cylindrical symmetry tubes drawing without inside guard, in UVD system.

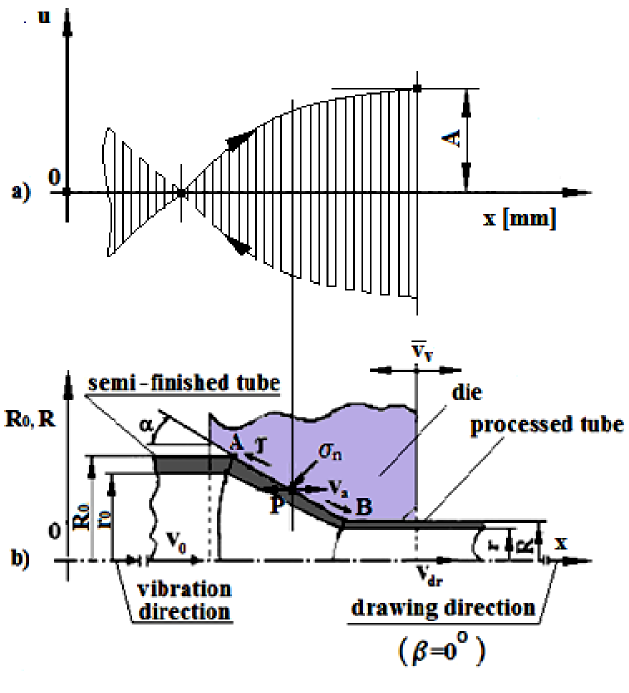

Fig. 1. Cylindrical symmetry tubes drawing without inside guard, in UVD system: a) waves oscillation; b) scheme of the ultrasonic activation: ——— running wave; --------- regressive wave.

The kinematics elements of the plastic deformation by drawing, based on the Severdenko Model (a Coulomb type friction), at the level of one oscillation time (T) are presented in [2, 4, 8, 9, 10].

It is considered that the wave movement *(u)* follows the motion law [4 and 10] given in the rel. (1):

$$u = A \cdot \sin\left(\frac{2\pi}{\lambda} \cdot x - \omega t\right) \tag{1}$$

where:
A – the amplitude of the waves oscillation;
$2\pi/\lambda$ – the wave factor;
λ – the length of the wave;
x – the movement direction of the wave (see Fig. 1.);
t – the movement time and ω represents the angular frequency ($\omega=2\pi f$, f – resonant frequency).

The vibratory rate is obtained using the time derivative of the motion, *(du/dt)*, with its maximum value $\bar{v}_v \equiv |\bar{v}_v| = 2\pi \cdot f \cdot A$, obtained when $\cos\left(\frac{2\pi}{\lambda} \cdot x - \omega t\right) = 1.0$.

Assuming the Severdenko Model in the developing of the reduction of the metal-tool contact mean friction, the ratio φ is given in the rel. (2), [2]:

$$\varphi = \frac{(T/2 + 2t_1) + (T/2 - 2t_1)}{(T/2 + 2t_1) - (T/2 - 2t_1)} \tag{2}$$

and represents the reduction degree of the mean friction in a point P, arbitrary chosen, at the metal-tool interface in the focus of the deforming area.

Equating $v_a = v_v$, [2, 4, 9, 10], it results t_1, the rel. (3):

$$t_1 = \frac{1}{\omega} \cdot \arccos \frac{v_a}{\bar{v}_v \cdot \cos\beta} \tag{3}$$

Using the rel. (3) for t_1 and $T=1/f$ in the rel. (2), it obtains the rel. (4):

$$\varphi = \frac{\pi}{2} \cdot \frac{1}{\arccos \dfrac{v_a}{\bar{v}_v \cdot \cos\beta}} \tag{4}$$

Substituting the slip rate of the metal (v_a) with the mean rate of drawing (v_{dr}), for the input / output sections in the focus of the plastic deformation area, it obtains the friction reduction on the entire metal-tool contact surface and the rel. (4) may be written as the rel. (5), [2, 4]:

$$\varphi = \frac{\pi}{2} : \arcsin \frac{v_{dr} \cdot \dfrac{\lambda_0 \cdot \cos\alpha + 1}{2\lambda_0 \cdot \cos\alpha}}{\bar{v}_v \cdot \cos\beta} \tag{5}$$

or the roughly value:

$$\varphi = \frac{\pi}{2} \cdot \frac{\bar{v}_v}{v_{dr}} \cdot \frac{2\lambda_0 \cdot \cos\alpha}{\lambda_0 \cdot \cos\alpha + 1} \cdot \cos\beta \tag{6}$$

where:

λ_0 – the wire elongation ($\lambda_0=S_0/S_1$; S_0 is the area of the initial section of the semi-finished tube; S_1 is the area of the processed tube).

During the ultrasounds drawing of the tubes, based on the plastic deformation kinematics and assuming the Coulomb type friction and the mean friction reversing as the Severdenko Model shows, the plastic deformation takes place in pulses: during the $T/2+2t_1$ time, it takes place the proper plastic deformation and during the $T/2-2t_1$ time, it takes place, at the most, the elastic deformation of the metal, [2, 4, 5, 6].

The plastic deformation in pulses also explains the reduction of the metal-tool contact friction when the die is places in the maximum of the wave oscillations and it is activated along the drawing direction.

The Severdenko Model can be applied for the drawing of the tubes made of strong cold deformable metallic materials / strong hardened metallic materials (whose angle of the die coning is 6 to 10º, [2, 4]), when it can be approximate the rate of drawing (v_{dr}) with the metal slip rate (v_a) along the generating line of the die cone, *A-B*, ($v_{dr}=v_a\cos\alpha$, for $\alpha\leq 10^o$, $\cos\alpha\rightarrow 1.0$, so v_{dr} becomes approximately equal to v_a), (see the Fig. 1.b)).

For a given plastic deformation process, λ_0, α_0 and β have constant values ($\lambda_0=S_0/S_1$; $\alpha\leq 10^o$ and $\beta=0^o$) meaning that the reduction degree of the mean friction (φ coefficient) depends on the ratio $v_{dr}/\bar{v}_v$ named the relative rate of drawing, see the rel. (5), [2, 4, 7, 8, 9].

3. Experimental researches on thin walls tubes made of stainless steel

3.1. Researched material

The researches use thin walls cylindrical symmetry tubes samples made of X5CrNi18-10 / EN 1008-3 / 2005, AISI 304 austenitic stainless steel, delivered by S.C. Rezistoterm S.R.L. from Iaşi, România; the samples have $D_0=5.50$ *mm*, $g_0=0.75$ *mm* and the length equal to *1200 mm*, one of the ends is rolling pointed and they are thermal treated by solution hardening / SH.

The semi-finished tubes belong to the class of those who were welded along the generating line and they were obtained by rolling classic technology from striped bands which are adequate profiled through many rolling-mill stands and then welded along the length of the tube, by WIG procedure.

The composition of the X5CrNi18-10 stainless steel was determined using an optical emission spectrometer, a BAIRD-DV6 type, made in USA in 2004. It is presented in Table 1:

Table 1. Composition of the X5CrNi18-10 steel spectrographic determined, [%])*.

C	Si	Mn	Ni	P	S	Cr	N
0.07	0.75	1.85	10.50	0.04	0.03	18.50	0.10

**) assuming EN 10088-3 / 2005*

3.2. Research method

The research method is conceived and developed to obtain, in the ultrasounds drawing plastic deformation, the reduction effect of the metal-tool contact friction / "the ultrasounds surface effect", based on the Severdenko Model, assuming a Coulomb type friction and considering "the reversing of the mean friction" during the $T/2-2t_1$ time, when $v_{dr}/\bar{v}_v << 1.0$, [2, 4, 7, 8, 10], at the level of a complete oscillation time (*T*), when the die is placed in the maximum of the wave oscillation and it is activated along the drawing direction / UVD system.

So, there are developed two main research directions about the influence of the ultrasound surface effect analyzed based on the relative rate of drawing ($v_{dr}/\bar{v}_v$):

(i) the influence of the ultrasound surface effect up the drawing force;

(ii) the influence of the ultrasound surface effect up the mechanical characteristics of resistance and plasticity.

The oscillator system used in the researches, having a particular construction and being realized at the Faculty of the Science and Materials Engineering of the "Gheorghe Asachi" Technical University from Iaşi, România, is dimensioned in $n\cdot\lambda/2$ (*n* is an integer number), [4, 9, 10].

The amplitude of the wave oscillation (*A*), at the die level and the resonant frequency *f*, are simultaneously measured using a device which was special realized for this aim – DMA, [10].

The chlorinated paraffin is used as lubricant in the plastic deformation process by drawing of the thin walls tubes made of X5CrNi18-10 stainless steel (classic technology or processing in ultrasound field).

The processing of the tube samples by the UVD procedure and by the classic technology – CT is realized using the experimental drawing bench BTL-01.000 (15 kN and hydro drive) which is in the plastic deformation research space of the Department of Technologies and Equipments for the Materials Processing, Faculty of the Science and Materials Engineering of the "Gheorghe Asachi" Technical University from Iaşi, România.

Fig. 2. Photo image of the tubes drawing bench BTL – 01.000 and of the ultrasonic equipment: 1 – control panel; 2 – oscillator system; 3 – guide columns; 4 – tube holding / drawing device; 5 – hydraulic cylinder; 6 – final level controller of the ultrasounds generator; 7 – ultrasounds generator IL 10 – 2.0 – 0.1.

There are used dies whose cores are made of metallic carbides (WC), from S.C. MECHEL S.A. Câmpia Turzii, which have the semi-angle of the die coning *α=10º*.

The Fig. 2 presents the photo image of the drawing bench BTL-01.000 and of the ultrasonic equipment (the main components).

The ultrasounds generator made in LTD "Ultrasonic Technique – INLAB" / www.utinlab.ru, 2008 generation, Russian Federation, have a 2000 W power and a 22.000 Hz resonant frequency.

3.2.1. Influence of the ultrasounds surface effect to the drawing force

The drawing force is the most important technological parameter at the tubes drawing processing in UVD system and in classic technology – CT.

Based on the Gavrilenko simplified relation for the drawing force, during the plastic deformation processing by drawing, in the case of the classic technology – CT, it can write the rel. (7), [1, 2, 4]:

$$F^{CT} = F_d + F_f = F_d \cdot \left(1 + \mu^{CT} \cdot ctg\alpha\right) \quad (7)$$

where:
F_d – proper force of the deformation;
F_f – friction;
μ^{CT} – friction coefficient (a Coulomb type friction).

During the tubes processing in UVD system, the rel. (7) becomes as the rel. (8) shows:

$$F^{UVD} = F_d \cdot \left(1 + \frac{\mu^{CT} \cdot ctg\alpha}{\varphi}\right) \quad (8)$$

The friction coefficient (μ^{CT}) in classic technology is given in the rel. (9) and in the case of the processing by drawing in ultrasounds field / UVD system, the friction coefficient (μ^{UVD}) is given in the rel. (10), [4]:

$$\mu^{CT} = \frac{\tau}{\sigma_n} \quad (9)$$

$$\mu^{UVD} = \mu^{CT}\left(1 - \frac{2}{\pi}\arccos\frac{v_{dr}}{\bar{v}_v}\right) \quad (10)$$

where:
τ – tangential / shear stress due to the friction;
σ_n – normal stress in an arbitrary chosen point, at the metal-tool interface; $\left|v_{dr}/\bar{v}_v\right| \le 1.0$.

In the case of the tubes drawing in ultrasound field / UVD system, it can realize the graphical variation of the coefficient *(φ)* – as a measure of the mean friction reduction – depending on the relative rate of drawing ($v_{dr}/\bar{v}_v$).

Because the measure of the mean friction reduction coefficient *(φ)* is the denominator of the rel. (8), it can conclude that $F^{UVD}<F^{CT}$.

The relative reduction of the drawing force / the UVD technology efficiency, can be determined using the rel. (11), [1, 2, 4]:

$$\Delta F = \frac{F^{CT} - F^{UVD}}{F^{CT}} \cdot 100[\%] \quad (11)$$

The variation of the mean friction reduction coefficient *(φ)* as a function of the relative rate of drawing ($v_{dr}/\bar{v}_v$), (see the rel. (5)), for the real experimental conditions of the plastic deformation in UVD system (thin walls tubes made of X5CrNi18-10 stainless steel; $D_0=5.50$ *mm* and $g_0=0.75$ *mm* drawn at $D_1=5.00$ *mm* and $g_1=0.65$ *mm*; *f=22.000 Hz; A=20 μm*; $\bar{v}_v=2.76$ *m/s*) is presented in the Fig. 3.

The rate of drawing variation between *0.01* and *0.90 m/s* is obtained using a frequency controller. By changing the frequency of the current it obtains a variation of the electromotor speed; so, it results a pressure variation of the hydraulic oil from inside of the BTL-01.000 drawing bench force cylinder.

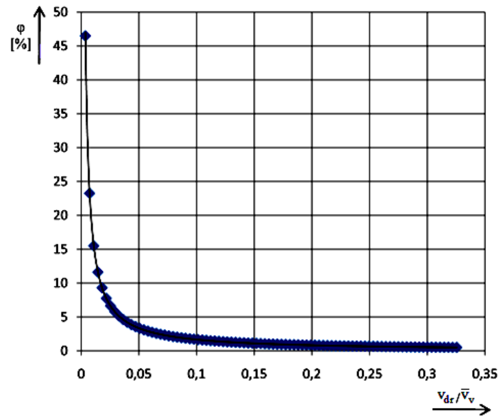

Fig. 3. Variation of the mean friction reduction coefficient (φ) as a function of the relative rate of drawing ($v_{dr}/\bar{v}_v$): D_0=5.50 mm; D_1=5.00 mm; α=10º; β=0º; λ_0 = 1.17; f = 22.000 Hz; v_{dr} = 0.01...0.90 m/s; $\bar{v}_v$ =2.76 m/s=ct.

The experimental research about the influence of the ultrasounds surface effect to the drawing force is analyzed in dependence to the relative rate of drawing ($v_{dr}/\bar{v}_v$).

This ratio ($v_{dr}/\bar{v}_v$) is very important in the processing of the thin walls tubes made of stainless steel, in ultrasound field because the rate of drawing (v_{dr}) defines the proper technological efficiency and the vibratory rate ($\bar{v}_v$) gives enough information about the equipment which produces and transfers the ultrasonic energy.

During the experimental process, the rate of drawing is kept at a constant value (v_{dr}*=2.0 m/min≈0.03 m/s*).

The vibratory rate is changed in the same time with the changing of the oscillation amplitude (*A*), in this way: *A=10 μm,* ($\bar{v}_v$)*=1.38 m/s; A=15 μm,* ($\bar{v}_v$)*=2.07 m/s* and *A=20 μm,* ($\bar{v}_v$)*=2.76 m/s.*

The relative rate of drawing ($v_{dr}/\bar{v}_v$) has the following values: 0.03; 0.02 and 0.01.

The drawing force (F^{CT} and F^{UVD}) is measured with the drawing cell, a CT-A-KN1C one, and its value is digital shown on the control panel.

The obtained experimental results about the influence of the relative rate of drawing ($v_{dr}/\bar{v}_v$) up the drawing force (F^{CT} and F^{UVD}) and up the technological efficiency (ΔF) are shortly shown in the Table 2, the Fig. 4. and the Fig. 5.

Table 2. Influence of the relative rate of drawing ($v_{dr}/\bar{v}_v$) up the drawing force (F^{CT}, F^{UVD}) and up the technological efficiency (ΔF)

No.	Ultrasonic parameters			Parameters of the drawing process								Force parameters		
	f, [Hz]	A, [µm]	$\bar{v}_v$, [m/s]	D_0, [mm]	g_0, [mm]	D_1,*) [mm]	g_1,*) [mm]	α, [°]	v_{dr}, [m/s]	$v_{dr}/\bar{v}_v$ -	δ_i,**) [%]	F^{CT}, [N]	F^{UVD}, [N]	ΔF, [%]
A	-	-	-	5.50	0.75	5.0	0.65	10	0.03	-	22	2220	-	-
B	22000	10	1.38	5.50	0.75	5.0	0.65	10	0.03	0.03	22	2220	1928	13.15
C	22000	15	2.07	5.50	0.75	5.0	0.65	10	0.03	0.02	22	2220	1857	16.35
D	22000	20	2.76	5.50	0.75	5.0	0.65	10	0.03	0.01	22	2220	1798	19.00

*) *$g_1/D_1=0{,}13$ – the category of the thin walls tubes*

**) *The degree of the section reduction* (δ_i) *is calculated using the relation:* $\delta_i = 1 - \frac{D_{med_i} - g_i}{D_{med_{i-1}} - g_{i-1}}$, [4]

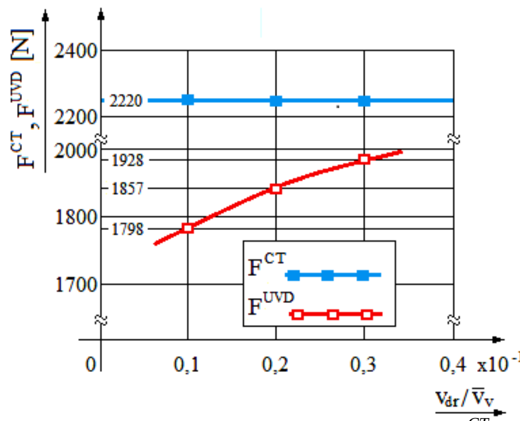

Fig. 4. Variation of the drawing force (F^{CT} and F^{UVD}) depending on the relative rate of drawing ($v_{dr}/\bar{v}_v$).

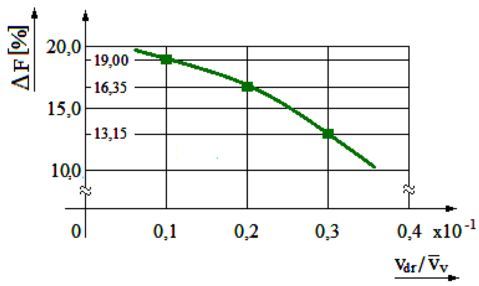

Fig. 5. Variation of the relative drawing force reduction (ΔF / technological efficiency) depending on the relative rate of drawing ($v_{dr}/\bar{v}_v$).

3.2.2. Influence of the ultrasounds surface effect to the mechanical characteristics of resistance and plasticity

Mechanical characteristics of resistance (R_m, $R_{p0,2}$) and plasticity (A_{10}) were determined by cold strain tension load using the universal machine for mechanical tests – model MTS 824.10, made in USA in 2002, a servo-hydraulic one, equipped with an electronic extensograph; the samples and the testing conditions are according to EN 10002-1-1995. The symbolizing of the sets of samples used in the research process is similarly with that presented in the Table 2: A – classic technology – CT; B – UVD technology / A=10µm; C – UVD technology / A=15µm; D – UVD technology / A=20µm and E – samples in an initial state / SH – without technological processing.

The cumulative diagram for the cold strain tension load of the five samples A, B, C, D, E is presented in the Fig. 6.

The experimental results of the cold strain tension load (the average of five determinations) both for tube samples classic processed – CT and ultrasounds processed / UVD system and for the initial state tube samples – SH, are presented in the Table 3.

The relative reductions of the mean breaking limit (ΔR_m), of the yield limit ($\Delta R_{p0,2}$), and of the elongation (ΔA_{10}) are calculated using the same relations as in the case of the drawing force relative reduction / UVD technological efficiency, see the rel. (11).

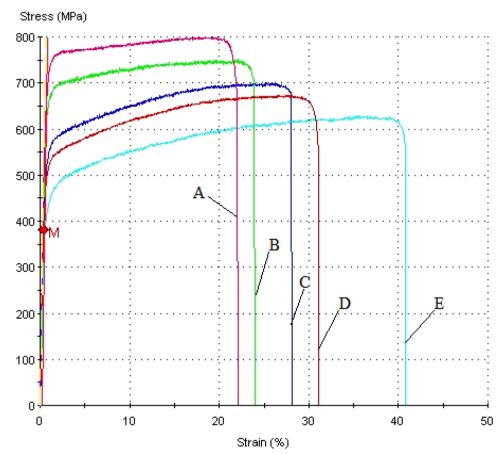

Fig. 6. Diagram for the cold strain tension load of the five samples A, B, C, D and E / SH.

Table 3. Experimental results for the cold strain tension load of the five samples A, B, C, D and E.

Sample symbol	D_0, [mm]	D_1, [mm]	$(v_{dr}/\bar{v}_v)$ -	R_m [MPa]	$R_{p0,2}$ [MPa]	A_{10} [%]	ΔR_m [%]	$\Delta R_{p0,2}$ [%]	ΔA_{10} [%]
A	5.50	5.0	-	800	620	23	-	-	-
B	5.50	5.0	0.03	780	590	24	2.50	4.83	5.0
C	5.50	5.0	0.02	760	570	29	5.00	8.06	20.0
D	5.50	5.0	0.01	740	550	33	7.50	11.29	30.0
E / SH	5.50	-	-	640	480	42	-	-	-

4. Conclusions

The paper presents the influence of the ultrasounds surface effect to the drawing force and to the mechanical characteristics of resistance and plasticity at the processing in ultrasound field / UVD system of the thin walls tubes made of X5CrNi18-10 / EN 1008-3 / 2005, AISI 304 austenitic stainless steel.

The experimental research is developed in two main directions:

(i) the influence of the ultrasound surface effect to the drawing force;

(ii) the influence of the ultrasound surface effect to the mechanical characteristics of resistance and plasticity (R_m, $R_{p0,2}$ and A_{10}).

The drawing force is measured with the drawing cell, a CT-A-KN1C one, (during the process of plastic deformation by drawing) and the mechanical characteristics of resistance and plasticity are determined by tension stress on samples made of classic processed tube (CT) and of ultrasonic processed tube (UVD) – accordingly with EN 10002-2-1995.

The obtained experimental results were analyzed in function of the relative rate of drawing $(v_{dr}/\bar{v}_v)$ – as a very important technological parameter in the case of the ultrasonic processing / UVD system because the value of the (φ) coefficient – as a measure of the metal-tool contact mean friction reduction (for a given drawing process λ_0 and α=const.) – depends on $(v_{dr}/\bar{v}_v)$.

The ratio $(v_{dr}/\bar{v}_v)$ is also important because the rate of drawing (v_{dr}) defines the proper technological efficiency and the vibratory rate $(\bar{v}_v)$ gives enough information about the equipment which produces and transfers the ultrasonic energy.

The most important results, expressed using the relative reductions (ΔF, ΔR_m, $\Delta R_{p0,2}$ and ΔA_{10}) are obtained when $(v_{dr}/\bar{v}_v)=0.01$ and they are: $\Delta F=19.13\%$, $\Delta R_m=7.50\%$, $\Delta R_{p0,2}=11.29\%$ and $\Delta A_{10}=30\%$.

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