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MODIFICATION OF MECHANICAL CHARACTERISTICS OF 10TiNiCr180 STAINLESS STEEL TUBES IN THE PROCESS OF DRAWING UNDER THE ACTION OF ULTRASONIC VIBRATIONS

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1. Introduction

Processing of stainless steel tubes by cold drawing is accompanied by cold hardening. Because of cold hardening accumulated at cold plastic deformation, the mechanical characteristics of resistance increase, while those of plasticity diminish.

In the case of cold drawing using the classical technology (CT) with a high degree of plastic deformation, the cold hardening can induce such defects as microcracks or fractures.

In order to diminish or even eliminate these defects developed when the CT is used, one can apply the technology of ultrasonic vibration drawing (UVD) [1].

The substantial decreasing of cold hardening for tubes processed in UVD system is caused by the “ultrasonic surface effect” or owing to the reduction of the metal-tool contact friction; this can be elucidated in terms of the “reversal of the mean friction force” [1, 2].

2. Particularities of tube processing by UVD technology

The principle scheme of the metal-forming area at tube processing by UVD technology is shown in Fig. 1. The following notations are used: D_0 is the external diameter of the rough tube; D is the external diameter of the processed tube; α is the semiangle of the die cone; τ is the shear stress; σ_n is the normal stress; and F^{UVD} is the drawing force at UVD technology. According to Fig. 1, any point P, arbitrarily chosen on the metal - tool interface, performs an oscillating motion with the maximum vibratory rate of the die v_v and a slip motion along the cone generatrix with the feed rate v_a [1].

The kinematic particularities of tube processing by UVD technology, as compared to the classical technology (CT), are schematically shown in Fig. 2. The resulting vector of the relative rate, determined by the composition of the rates v_v and v_a, changes the direction of displacement of the arbitrary point P along the cone generatrix as follows: during the interval $T/2 - 2t_1$ both the point P and the metal move in the same direction, and during $T/2 + 2t_1$ they move in the opposite directions. Assuming the Coulomb type friction at the metal - tool contact, the above model represents the principle of the “reversion mechanism of the average friction force”, since the friction force becomes positive during $T/2 - 2t_1$ interval and negative during $T/2 + 2t_1$ interval [1, 2].

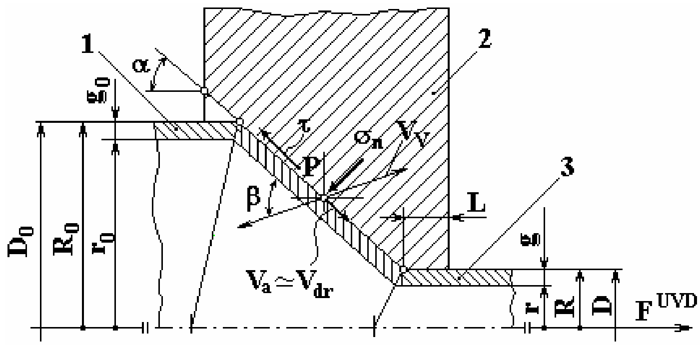

Fig. 1. Principle scheme of the metal–forming area at tube processing by UVD technology: 1 – rough tube; 2 – die; 3 – processed tube

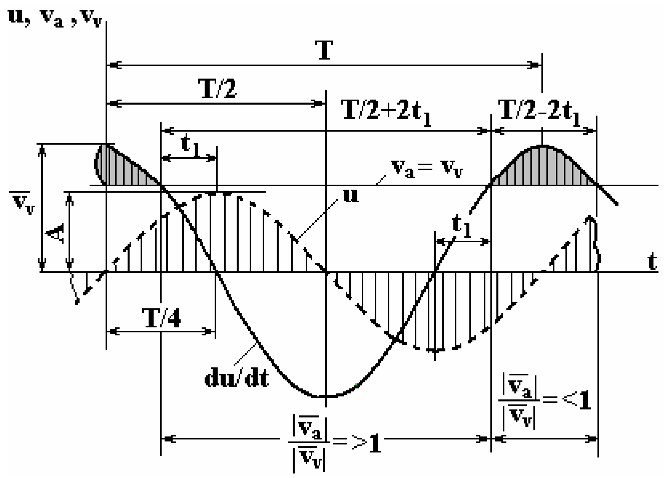

Fig. 2. Kinematic elements of the plastic deformation process using UVD technology: u – wave displacement; v_{dr} – drawing rate; v_v – vibration rate of the die

In the case of drawing of tubes made of work hardenable metallic materials, the cross section can be reduced to a small degree only, so the semiangle of the die should amount to $\alpha = 6–12^\circ$. Considering that $v_a = v_{dr} \cos \alpha$, it is a good approximation to assume $\cos \alpha \to 1$ and $v_a \cong v_{dr}$. Under these circumstances, we can write the friction coefficient at UVD technology as [1]:

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

where μ^{CT} is the friction coefficient at the classical technology and $v_{dr} / \bar{v}_v \leq 1$ is the relative drawing rate, where $\bar{v}_v = max\left(du / dt\right) = max[\,dA\,sin\left(2\pi ft\right) / \,dt\,] = 2\pi fA$ is the maximum vibration rate of the die (A and f is the amplitude and frequency of the die oscillations, respectively).

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

3. 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 axially symmetric conical motion into the deformation focus as illustrated in Fig. 3.

The geometrical elements are as follows: R_0 and R are the external radii of the rough and processed tube, respectively; r_0 and r are the internal radii of the rough and processed tube, respectively; g_0 and g are the wall thicknesses of the initial and final tube, respectively; β_0 is the initial cone semiangle and β_f is the final cone semiangle [3].

The kinematic elements are as follows: v_0 is the initial rate of the tube; v is the rate in the deformation focus; v_{dr} is the drawing rate. F^{UVD} and σ^{UVD} represent the drawing force and stress, respectively.

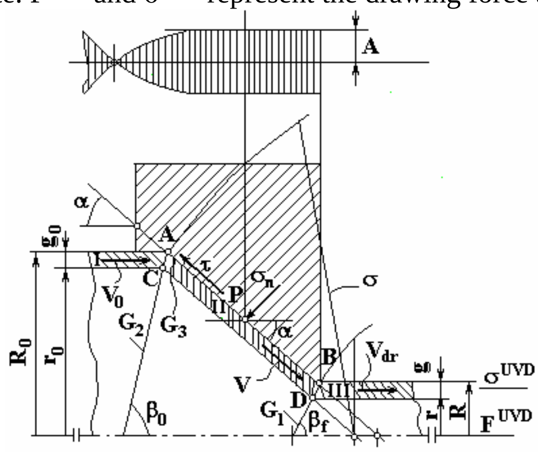

Fig. 3. Geometrical and kinematical elements of the axially symmetric conical motion; solid line – progressive wave; dotted line – regressive wave

The rest of the parameters have the same meaning as above. Moreover, the following assumptions are adopted: (i) the metallic material is totally incompressible; (ii) the die is a rigid body; (iii) the metal deformation is performed according to the Von Mises flowing condition; (iv) the kinematical rate field provides a Bernoulli-type continuity; (v) at the metal-tool interface, the Coulomb-type friction is produced that is considered constant for a given drawing process; (vi) at the oscillating system level, only longitudinal elastic waves act under the stationary regime (forming nodes and antinodes), and (vii) the plastic deformation process is isothermal, the thermal effects of the internal friction being neglected. With the above assumptions and according to Fig. 3, we can calculate the drawing force using the relationship:

$$F^{UVD} = \pi\left(R^2 - r^2\right)\sigma^{UVD} \quad . \tag{2}$$

For the geometry and kinematics of axially symmetric conical motion, schematically shown in Fig. 3, the following coefficients are introduced [4]:

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

The tube has been divided into three zones with continuous rate fields: zones I and III that have a uniform axial rates, since the drawing rate coincides with the tube symmetry axis and zone II (deformation area) where the rate direction makes an angle α with the symmetry axis.

Zone II, characterized by the metal flow parallel to the die active surface, is limited by conical surfaces G_1 and G_2, represented by segments BD and AC and defined by the angles β_f and β_0, respectively, and is externally limited by surface G_3.

On the basis of the experimental results, it was observed that the thickness of the tube wall decreases only at the beginning of the proper plastic deformation. This means that, taking into account the tube geometry, the deformation area, the angles β_0 and β_f can be determined as:

$$\beta_0 = (\pi - \alpha)/2 \tag{4}$$

and:

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

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

$$\frac{v_0}{v_{dr}} = \frac{R^2 - r^2}{R_0^2 - r_0^2} = K_1^2\frac{1-K_2^2}{1-K_3^2} . \tag{6}$$

At the level of the three surfaces that limit the deformation area, the rate discontinuities can be written as:

$$\Delta v_1 = v_{dr}\frac{\sin\alpha}{\sin\left(\alpha+\beta_f\right)}, \text{ on surface } G_1 \tag{7}$$

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

$$\Delta v_3 = v = v_{dr}\frac{R^2 - r^2}{R_0^2 - \left(R_0 - g_0\cos\alpha\right)}\cos^2\alpha, \text{ on surface } G_3. \tag{9}$$

During the drawing, the total consumed power must compensate the losses produced: (i) by the proper plastic deformation ($\dot{W}_d$); (ii) by the shear due to the rate discontinuities on surfaces G_1 and G_2 ($\dot{W}_{G_{1,2}}$), and (iii) by friction on surface G_3 ($\dot{W}_f$).

The power consumed by the plastic deformation is determined as:

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

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

$$\varepsilon_{pp} = ln\frac{R-r}{R_0 - r_0}ln\left(K_1K_4\right) \tag{11}$$

$$\varepsilon_{\theta\theta} = ln\frac{R+r}{R_0+r_0} = ln\left(K_1 K_5\right) \tag{12}$$

$$\varepsilon_{ZZ} = -\left(\varepsilon_{RR} + \varepsilon_{\theta\theta}\right) \tag{13}$$

$$\varepsilon_{R\theta} = \varepsilon_{RZ} = \varepsilon_{\theta Z} = 0. \tag{14}$$

In the Eq. (10), σ_c is the yield stress of the deformed metal and $\dot{V}$ is the volume rate:

$$\dot{V} = \pi v_{dr}\left(R^2 - r^2\right). \tag{15}$$

Consequently, the power consumption due to plastic deformation becomes:

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

The power consumed while crossing the surface G_1 is as follows:

$$W_{G_1} = \int_{SG_1} \tau \Delta v_1 ds \tag{17}$$

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

$$SG_1 = \pi\left(R^2 - r^2\right)/\sin\beta_f\ . \tag{18}$$

Therefore, the power consumed while crossing the surface G_1 becomes:

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

Similarly, the power consumed while crossing the surface G_2 is:

$$\dot{W}_{G_2} = \left(\sigma_3/\sqrt{3}\right)v_0 \cdot 2\sin\left(\alpha/2\right)\cdot\pi\left[\left(R_0^2 - r_0^2\right)/\sin\beta_0\right] = \left(2/\sqrt{3}\right)\sigma_c \pi v_{dr} R^2\left[1-\left(r/R\right)^2 tan\left(\alpha/2\right)\right]. \tag{20}$$

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

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

The 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 can be written as:

$$ds = \frac{2\pi}{\sin\alpha} RdR, R \in \left[R, R_0\right]. \tag{22}$$

The normal stress can be determined on the basis of the Sach relationship:

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

Taking into account the above relationship, the power consumed owing to the friction on surface G_3 becomes:

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

therefore:

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

$$= \mu^{UVD}\sigma_c\left[ln\left(\frac{R_0}{R}\right)^2 - 1\right]v_{dr}\left(R^2 - r^2\right)\frac{\pi\cos\alpha}{g_0\sin\alpha}\left[R - \frac{g_0}{2}\cos\alpha\cdot ln\left(R - \frac{g_0}{2}\cos\alpha\right)\right] =$$

$$= \frac{\pi\mu^{UVD}\sigma_c}{g_0}v_{dr}\left(R^2 - r^2\right)\left[ln\left(\frac{R_0}{R}\right)^2 - 1\right]\frac{\cos\alpha}{\sin\alpha} \tag{25}$$

$$\left[\left(R_0 - R\right) - \frac{g_0}{2}\cos\alpha\cdot ln\frac{R_0 - \frac{1}{g_0}\cos\alpha}{R_0 - \frac{1}{2}g\cos\alpha}\right] = \pi\mu^{UVD}\sigma_c v_{dr}R^2\left(1 - K_2^2\right)Q_2$$

where:

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

From the balance of the total consumed power at UVD technology, it follows that the drawing stress can be expressed:

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

where:

$$Q_1 = \sqrt{\varepsilon_{RR}^2 + \varepsilon_{\theta\theta}^2 + \varepsilon_{RR}\varepsilon_{\theta\theta}} + \frac{sin\,\alpha}{2\sin\beta_f\sin\left(\alpha + \beta_f\right)} + tan\frac{\alpha}{2}\ . \tag{28}$$

Substituting Eq. (27) into Eq. (2), we obtain for the drawing force:

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

In the case of the classical technology (CT), the drawing stress can be determined from Eq. (27):

$$\sigma^{CT} = \frac{2\sigma_c}{\sqrt{3}}Q_1 + \frac{2\sigma_c}{\pi}\mu^{CT}Q_2\ . \tag{30}$$

This allows to determine the drawing force as:

$$F^{CT} = \pi\left(R^2 - r^2\right)\sigma^{CT}\ . \tag{31}$$

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

$$C = \frac{S\sigma_r}{F} \tag{32}$$

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

4. Experiments and results

The experiments were carried out at the beneficiary partner facility SC REZISTOTERM SRL, Iasi (CEEX Contract no. 293/2006 [4]). For the research, 10TiNiCr180 stainless steel tubes coated with magnesium oxide, which are used in electric heaters, were processed in a UVD system. It was assumed that in the drawing process of the tubes, the magnesium oxide coating does not influence the deformation process.

The experiments were carried out using the ultrasonic equipment EUS produced at the Institute of Technical Physics (IFT), Iasi [4].

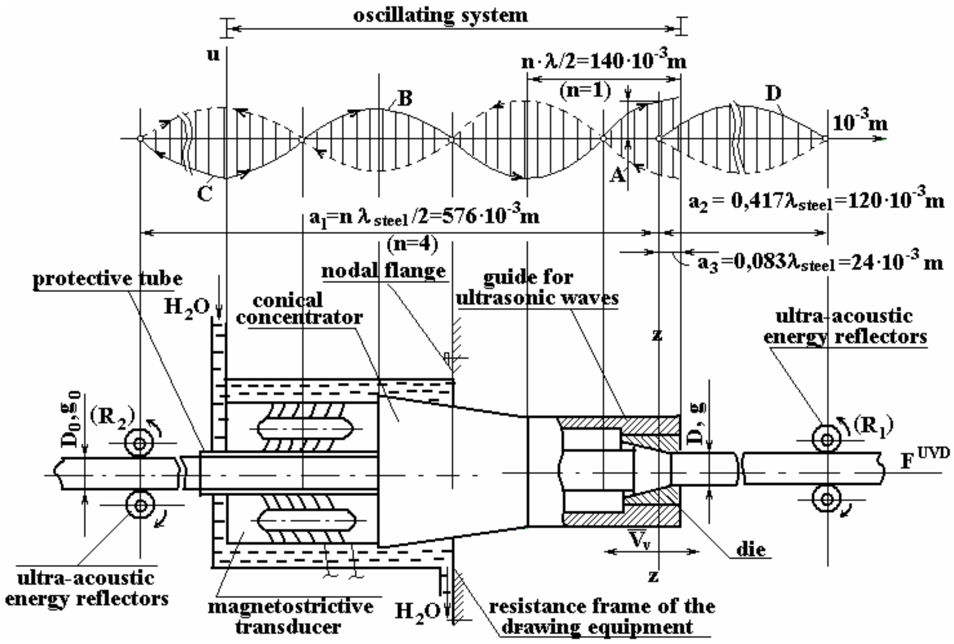

Fig. 4. Constructive functional scheme for oscillating system used in the experimental process: a) wave oscillations; b) scheme of the UVD installation

The drawing process was performed using the longitudinal bench provided by the SC REZISTOTERM SRL, Iasi.

For the experiments, the samples were used made of 10TiNiCr180/EN1.4301 stainless steel with D_0=5.50 mm, g_0 = 0.70 mm, and the length of 1200 mm; one of the ends was embossed by cold rolling and heat treated by solution quenching (SQ). The chemical composition of 10TiNiCr180 steel determined spectrographically is presented in table 1.

Table 1. Spectrographically determined chemical composition of 10TiNiCr180 steel, %

C	Mn	Si	P	S	Cr	Ni	Ti
0.03	1.4	0.5	0.05	0.06	19.4	10.8	0.7

The microscopic structure of the steel subjected to cold plastic deformation is composed of polyhedral crystals of austenite in the form of twinned crystals with discrete ferrite separations within the limits of the crystal. Magnesium oxide used as insulator was obtained by electric melting with a content of minimum 92% MgO with granulation of 0.045–0.43 mm.

Activation of the auger die by ultrasounds was performed at amplitudes of 15, 20 and 25 μm. This lead to vibration velocities of 1.64; 2.19 and 2.74 m/s (see relationship $\overline{v}_v = 2\pi fA$ in Section 2), the load resonance frequency (f) of the oscillating system was 17500 Hz.

Table 2. The influence of the relative drawing velocity ($v_{dr}/\overline{v}_v$) on the deformation force (F^{UVD}) and the economic efficiency at processing of 10TiNiCr180 stainless steel tubes in UVD system: f = 17500 Hz, A = 25 μm ($\overline{v}_v = 2.74$ m/s)

No.	Kinematic characteristics		Technological characteristics						ΔF, %
	CT	UVD	CT			UVD			
	V_{dr}, m/s	$v_{dr}/\overline{v}_v$	F^{CT}, N	σ^{CT}, MPa	σ^{CT}/σ_c, -	F^{UVD}, N	σ^{UVD}, MPa	σ^{UVD}/σ_c, -	
1	0.06	0.02	1332	150	0.46	940	106	0.33	29.42
2	0.10	0.03	1332	150	0.46	970	110	0.34	27.17
3	0.13	0.04	1332	150	0.46	1008	114	0.35	24.32
4	0.16	0.05	1332	150	0.46	1053	119	0.37	20.94

The drawing force was determined with ultrasounds or without them using a DT–106.00 load cell and N2314 Bridge [5]. The experimental results regarding the influence of the relative drawing velocity ($v_{dr}/\bar{v}_v$) on the deformation force (F^{UVD}) and the economic efficiency (DF) at processing of 10TiNiCr180 stainless steel tubes is presented in table 2.

Table 3. Experimental results obtained at the SC REZISTOTERM SRL, Iasi using CT and UVD system

No.	Sample types	Classical technology (CT)						Technical and economic efficiency of UVD system					
		F, N	C	R_a, μm	$R_{p0.2}$, MPa	R_m, MPa	A_5, %	ΔF, %	ΔC, %	ΔR_a, %	$\Delta R_{p0.2}$ %	ΔR_m, %	ΔA_5, %
1	A, Classical technology (CT)	1334	4.77	1.4	349	509	33.20	-	-	-	-	-	-
2	B, UVD system, A = 15 μm	1074	5.82	1.2	346	498	33.6	19.49	18.04	14.28	0.86	2.16	1.19
3	C, UVD system, A = 20 μm	1015	6.03	0.8	343	488	34.0	23.91	20.89	42.85	1.71	4.12	2.35
4	D, UVD system, A = 25 μm	942	6.33	0.6	328	459	35.4	29.38	24.64	57.14	6.01	9.82	6.21
5	E, Initial state (Solution quenching)	-	-	-	320	486	38	-	-	-	-	-	-

The following mechanical properties were analyzed: the average ultimate resistance (R_m), the yield point ($R_{p0,2}$), the microhardness ($HV_{0.1}$) and the breaking elongation (A_5). In order to determine the mechanical characteristics R_m, $R_{p0.2}$ and A_5, the tensile tests were carried out according to SR EN 10002 – 1/1995 standard (identical with the European standard SR EN 10002–1/1990). The tensile tests were made on a MTS 810.24/SUA machine, precision class 0.5 with the force velocity of 20 mm/min.

The microhardness $HV_{0.1}$ (STAS 7057) was determined on a PMT-3 hardness testing machine; the average values were obtained as a result of five measurements. The results of the experimental research performed at the beneficiary partner P2 SC REZISTOTERM SRL, Iasi (CEEX Contract no. 293/2006 [4]), using two technologies (CT and UVD system) are presented in Fig. 5 and 6 and in Table 3. The variation of force parameters (F^{CT}, F^{UVD} and DF) is shown in Fig. 5, and the variation of mechanical characteristics of resistance and plasticity (ΔR_m, $\Delta Rp_{0.2}$ and ΔA_5) is shown in Fig. 6.

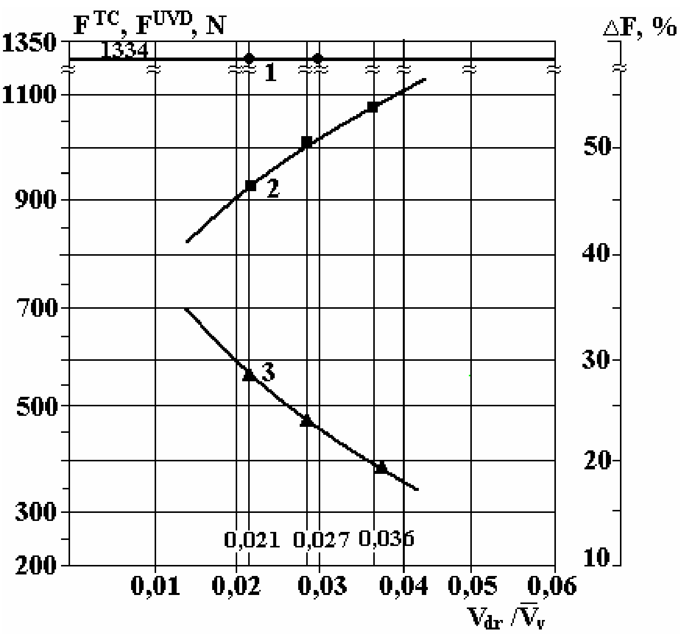

Fig.5. Technologic efficiency (ΔF) and variation of force parameters at processing of 10TiNiCr180 stainless steel tubes using the classical technology CT (F^{CT}) and UVD system (F^{UVD})

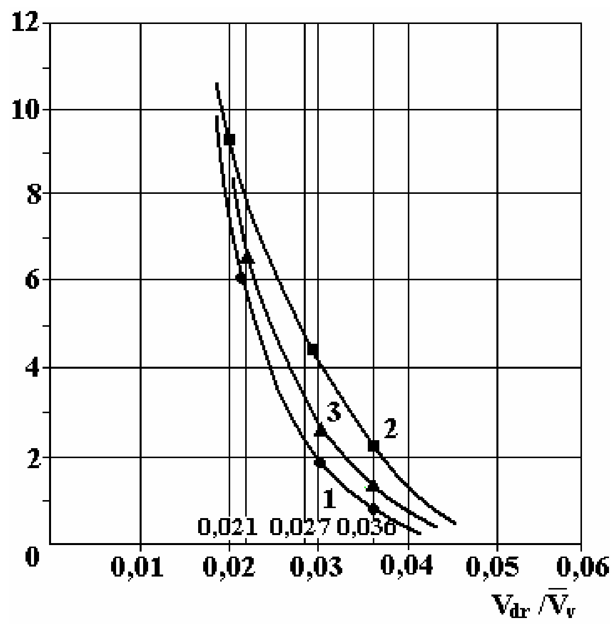

Fig.6. Variation of relative reductions of mechanical characteristics of resistance and plasticity(ΔR_m, $\Delta Rp_{0.2}$, ΔA_5)

5. Conclusions

The modification of mechanical characteristics of resistance and plasticity at drawing of 10TiNiCr180 stainless steel tubes in an ultrasonic field was analyzed as a function of the relative drawing velocity ($v_{dr}/\overline{v}_v$).

We obtained the decreasing of mechanical characteristics of resistance ($R_{P0.2}^{UVD}$ and R_m^{UVD}), much greater extension (A_5^{UVD}), increasing of drawing safety (C) and surface quality while using the UVD method in comparison with the classical technology. The maximum relative reductions were obtained for $v_{dr}/\overline{v}_v = 0.021$, namely, $\Delta R_m = 9.82\%$, $\Delta A_5 = 6.21\%$, $\Delta C = 24.64\%$, and $\Delta R_a = 57.14\%$.

High values for ΔR_a were obtained owing to the die vibration that increases when the vibration velocity increases. Application of the UVD method increases the drawing rate; at the same time the productivity increases by about 30%, the safety increases by about 25% with the plasticity reserves of approximately 6%.

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Summary

The paper presents the results of the experimental research concerning modification of mechanical characteristics of resistance and plasticity in the process of drawing of 10TiNiCr180 stainless steel tubes with and without ultrasonic vibrations. The experiments were performed in the framework of the CEEX project (Excelence Research Program, Ministry of Education, Research and Innovation of Romania), Contract no. 293/2006. Modification of mechanical characteristics of resistance and plasticity is analyzed for the tube samples processed using the classical technology (CT) or ultrasonic vibration drawing (UVD) depending on the relative drawing velocity ($v_{dr}/\overline{v}_v$).