Influence of the plastic deformation kinetics during the ultrasonics drawing of the metallic wires able to be hardened

B. – L. GAVRILĂ, M. SUSAN, E. CHIRILĂ*, V. BULANCEA, M. – L. CRAUS[a]
The "Gheorghe Asachi" Technical University from Iaşi, Bd. D. Mangeron 67, 700050 Iaşi, România
[a]*Joint Institute for Nuclear Researches from DUBNA – Russian Federation*

The paper presents some researches about the influence of the plastic deformation kinetics, respectively, of the relative rate of drawing, on the force parameters and on the resistance and plasticity mechanical characteristics, during the ultrasonics drawing of the cylindrical symmetry metallic wires able to be hardened, when the die is placed in the maximum of the waves oscillations and it is activated along the drawing direction. The modifications of the force parameters and of the resistance and plasticity mechanical characteristics are considered to be based on "the ultrasounds surface effect" accepting the phenomenon of the mean friction reversal in a complete time of the oscillation, T - Severdenko's model. As a reduction measure of the mean friction at the metal-tool contact is the coefficient *φ*.

(Received April 27, 2012; accepted October 30, 2012)

Keywords: Ultrasonics drawing process, Hardening process, Plastic deformation kinetics, Relative rate of drawing, Ultrasounds surface effect

1. Introduction

The wires drawing process is a classical technology – CT, specific for the manufacturing of the wires by cold plastic deformation (the drawing process takes place at the environmental temperature).

The plastic deformation by cold drawing is characterized by hardened / cold-work hardening under the stress effect; it goes to the increase of the resistance characteristics and to the decrease of the plasticity characteristics, [1]. When the plastic deformation process takes place in a strong way, the disturbance of the metallic material integrity (smooth fractures) may happen, so, the drawn products become non-normal.

The paper presents the influence of the plastic deformation kinetics on the force parameters and on the resistance and plasticity mechanical characteristics, during the ultrasonics vibration drawing – UVD process, of the metallic wires which have a cylindrical symmetry, strong hardened by cold plastic deformation.

It was considered "the ultrasounds surface effect"/ "the reduction of the metal-tool contact friction effect", when the die is placed in the maximum of the waves oscillations /antinodes and it is activated along the drawing direction, Fig. 1.

The ultrasonics energy reflectors, placed at certain distances (see Chapter 3of this paper), must generate a stable system of standing waves (with antinodes and vertexes of the waves oscillations) into the wire, [2, 3, 9].

Experimental researches were made using C 80 steel tyre cord, frequently used at the pull cables manufacturing.

There were problems when the steel wires used for the cables manufacturing must be included in one of the certain resistance grade, because, according with ISO 2408, these must be delivered only in a hardened state (hardened by cold drawing).

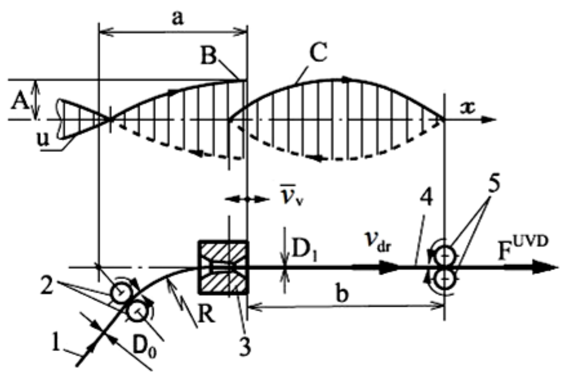

Fig. 1. Scheme of the ultrasonics drawing – UVD: 1 – semi-finished wire; 2, 5 – ultrasonics energy reflectors; 3 – die; 4 – drawn wire; x – propagation direction of the waves; A – amplitude of the waves oscillations; B – waves oscillations at the oscillator system level; C – waves oscillations of the drawn wire; D_0, D_1 – diameters of the semi-finished wire and, respectively, of the drawn wire; R – curvature of the semi-finished wire; u – waves motion; $\bar{v}_v$ – maximum value of the die vibratory rate; v_{dr} – rate of drawing; F^{UVD} – drawing force, UVD process; a, b – positioning distances of the ultrasonic energy reflectors: — progressive wave; ----- regressive wave.

The cross section shape of the usually pull cables with double-normal construction, is presented in Fig. 2, [1].

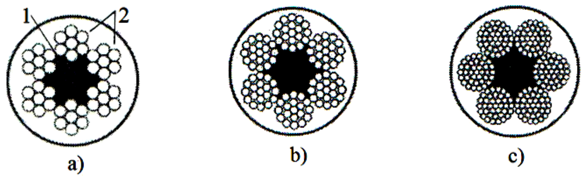

Fig. 2. Cross section shape of the pull cables, double-normal construction, [1]: a) 1570H6x7(1+6); b) 1770H6x19(1+6+12)); c) 1960H6x37(1+6+12+18); 1 – cable core; 2 – cable strand;*) 1770 – resistance breaking, MPa; H – textile core; 6 – number of strands; 19 – number of wires; (1 – number of middle wires; 6 – number of wires in the second row; 12 – number of wires in the last row).*

2. Plastic deformation kinetics during the ultrasonics drawing of the metallic wires with cylindrical symmetry

The hypothesis of the plastic deformation process are: the metallic material is incompressible; the die is a rigid body; the metal deformation is realized in the von Misses flowing conditions; the rates field provides a Bernoulli type continuity; the metal-tool contact friction is a Coulomb type one and it is constant during the certain drawing process; at the oscillator system level there are only longitudinal elastic waves as standing waves (with antinodes and vertexes); the plastic deformation process is an isothermal one.

The plastic deformation kinetics, the theoretical model, is based on the Severdenko's model, as its completion, [2], considering the mean friction reversal: the friction is positive$\left(F_f^+\right)$, in time *T/2 – 2t₁*, when $|\vec{v}_a| < |\vec{v}_v|$ and it is negative$\left(F_f^-\right)$, in time *T/2 + 2t₁*, when $|\vec{v}_a| > |\vec{v}_v|$, considering a complete time of the oscillation, (T), Fig. 3, [2, 3, 4].

Fig. 3 shows that, in the deformation area, the metal realizes isochronous oscillations with a certain vibratory rate, $|\vec{v}_v|$ which is superposed over the constant slip rate, $|\vec{v}_a|$.

As the previous shows, a certain point *P*, arbitrary chosen in the plastic deformation area, at the metal-tool interface, has two motions: one of them is a continuous feed along the die cone generatrix, $|\vec{v}_a|$ and the other, is a vibratory one, $|\vec{v}_v|$. The friction vector, $|\vec{F}_f|$, in the case of the drawing process as a classical technology – CT, is subtended to the direction of the metal moving velocity, $|\vec{v}_a|$ and, in the case of the ultrasonics drawing process – UVD, it is subtended to the direction of the resultant velocity vector (the composition of $|\vec{v}_v|$ and $|\vec{v}_a|$). Considering the ultrasonic drawing process – UVD, the resultant of the relative rate will change the movement direction of point *P* in correlation with the sense of the two rates vectors, $|\vec{v}_v|$ and $|\vec{v}_a|$ and with these two vectors sizes of projections on the friction direction *A – B*, (see detail "Y"). During *T/2 – 2t₁* time, as a part of the complete oscillation time, *T*, the motion of point *P* is identically with the metal motion, when the vibratory rate vector projection on the friction direction *A – B* is bigger than the feed rate vector projection on the same direction, $|\vec{v}_v| > |\vec{v}_a|$; during *T/2 + 2t₁* time, as a part of the complete oscillation time, *T*, the motion of point *P* has an opposite sense with the metal motion, when the vibratory rate vector projection on the friction direction *A – B* is smaller than the feed rate vector projection on the same direction, $|\vec{v}_v| < |\vec{v}_a|$.

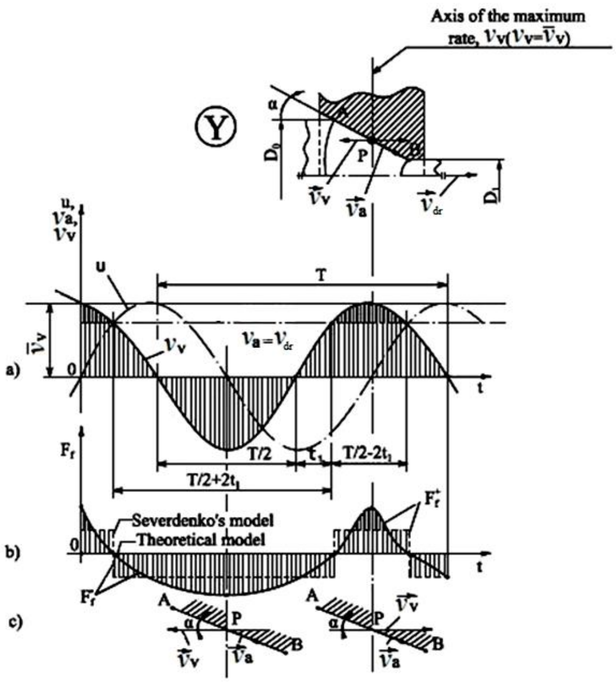

Fig. 3. Plastic deformation kinetics during the ultrasonics drawing/UVD, [2, 4]: a) waves motion, (u), v_a – slip rate of the metal, v_v – vibratory rate of the die, $\bar{v}_v$ – vibratory rate of the die, maximum value; v_{dr} – rate of drawing; b) Severdenko's model – classical case and theoretical model; c) directions of the rate vectors, $\vec{v}_v$ and $\vec{v}_a$, in point P (detail "Y").

Considering that the drawing process of the strong hardenable metallic wires takes place with the condition of the half-angle of the die cone, $\alpha \le 10^0$, [4], so, $\cos\alpha \to 1$, we have made the approximation $|\vec{v}_a| \cong |\vec{v}_{dr}|$, because $|\vec{v}_{dr}| = \cos\alpha \cdot |\vec{v}_a|$.

Considering that the law of the waves motion is, rel. (1):

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

the vibratory rate of the die is the motion time derivative, rel. (2):

$$\frac{du}{dt} = A \cdot \omega \cdot \cos\left(\frac{2\pi}{\lambda} \cdot x - \omega t\right) \quad (2)$$

where: $\cos\left(\frac{2\pi}{\lambda} \cdot x - \omega t\right) = 1$; $\left(\frac{2\pi}{\lambda}\right)$ – wave factor; $\omega = 2\pi \cdot f$ – angular frequency.

Therefore, the maximum of the vibratory rate, $|\vec{v}_v|$ is, rel. (3):

$$\bar{v}_v = 2\pi \cdot f \cdot A \quad (3)$$

where: A – amplitude of the oscillation, previously noticed; f – resonant frequency at the level of the graded cylindrical concentrator/ for work (see Fig. 5).

The ratio $\left|\frac{\vec{v}_{dr}}{\vec{v}_v}\right|$ is also known as named "the relative rate of drawing", [3]. So, the relative rate of drawing, $\left|\frac{\vec{v}_{dr}}{\vec{v}_v}\right|$, defines the plastic deformation kinetics of the metal, based on the Severdenko's model and accepting the existence of "the reversal of the mean friction (F_f^-)" phenomenon, at the level of an oscillation complete time, *(T).*

In other words, in the ultrasonics drawing process – UVD case, the plastic deformation takes place in pulses: during $T/2 + 2t_1$ time, the proper plastic deformation takes place; during $T/2 - 2t_1$ time, it will take place an elastic deformation of the metal, at the most. For example, it can say that, for 22000 Hz frequency, it will produce 22000 attachments and detachments between the plastic deformed metal and the die, in one second. The plastic deformation in pulses, mostly explains the reduction of the metal-tool contact mean friction, in the case of the ultrasonics drawing process – UVD case.

Assuming the Severdenko's model in the explaining of the reduction of the metal-tool contact mean friction, the ratio φ is, rel. (4), [3, 5, 7]:

$$\varphi = \frac{(T/2 + 2t_1) + (T/2 - 2t_1)}{(T/2 + 2t_1) - (T/2 - 2t_1)} \quad (4)$$

The ratio φ presented in rel. (4) represents the degree of the mean friction reduction in point *P*, considered to be placed at the metal-tool interface, in the focus of the deforming area.

Equating $v_{dr} = v_v$, it results t_1, rel. (5):

$$t_1 = \frac{1}{\omega} \cdot \arccos \frac{v_{dr}}{v_v \cdot \cos\beta} \quad (5)$$

Using the rel. (5) for t_1 and $T = 1/f$ in rel. (4), it will obtain rel. (6):

$$\varphi = \frac{\pi}{2} \cdot \frac{1}{\arccos \frac{v_{dr}}{v_v \cdot \cos\beta}} \quad (6)$$

Considering the mean value of the rate of drawing (based on the continuity equation of the metal flow), for the input / output sections in the focus of the plastic deformation area, the degree of the mean friction reduction (φ), on the entire metal-tool contact surface, is given by the rel. (7):

$$\varphi = \frac{\pi}{2} : \arccos \frac{v_{dr} \cdot \frac{\lambda_i \cdot \cos\alpha + 1}{2\lambda_i \cdot \cos\alpha}}{\bar{v}_v \cdot \cos\beta} \quad (7)$$

where: β – die activation angle, $\beta = 0^0$ along the drawing direction; λ_i – wire elongation per pass, given by the rel. (8), [1]:

$$\lambda_i = S_0 / S_1 = \left(\frac{D_0}{D_1}\right)^2 \quad (8)$$

Using the Gavrilenko's simplified relation for the calculation of the force in the plastic deformation by drawing processes, classic technology – CT, it results rel. (9), [3]:

$$F^{CT} = F_d + F_f = F_d \cdot (1 + \mu \cdot ctg\alpha) \quad (9)$$

where: F_d – proper force of deformation; F_f – friction; μ – friction coefficient (Coulomb type friction).

In the case of the ultrasound drawing process – UVD, rel. (9) becomes rel. (10):

$$F^{UVD} = F_d \cdot \left(1 + \frac{\mu \cdot ctg\beta}{\varphi}\right) \quad (10)$$

In other words, in the case of the ultrasonics drawing process – UVD, the friction (F_f) decreases with the size of the coefficient φ. For example, Fig. 4. shows the variation $\varphi = f(v_{dr}/\bar{v}_v)$ for a certain drawing process UVD.

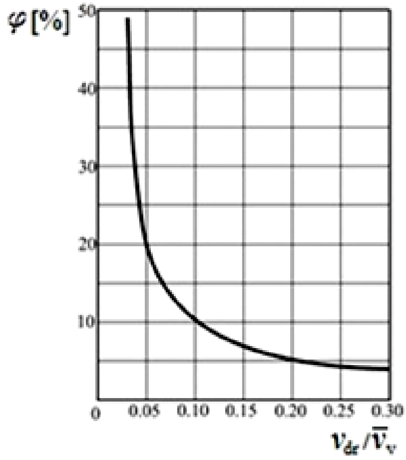

Fig. 4. Variation of the coefficient φ depending on the relative rate of drawing $(v_{dr}/\bar{v}_v)$, for a certain drawing process in the following conditions: D_0=3.50 mm; D_1= 3.00 mm; $\alpha = 8^0$; δ_i = 19 %; $\beta = 0^0$; f = 22000 Hz; λ_i=1.36; v_{dr}=0.06 m/s; A=25 μm; $\bar{v}_v$ =3.45 m/s.

The vibratory rate of the die is given by the rel. (3) and the reduction degree of one pass section, δ_i, is given by the rel. (11), [1, 3]:

$$\delta_i = \left[1 - \left(D_1/D_0\right)^2\right] \cdot 100\,\% \qquad (11)$$

3. Experimental procedure

Our researches have used steel tyre cord C80 (delivered by S.C. CORD S.A. Buzău, România), with cylindrical symmetry, hardened by drawing, between two processes for structure restoration, going from D_0=5.50 mm to D_1=5.00 mm, D_2=4.50 mm, D_3=4.00 mm and, finally, D_4=3.50 mm.

The total reduction of the section, δ_{tot}, is given by the rel. (12):

$$\delta_{tot} = 1 - (1 - \delta_1)(1 - \delta_2)(1 - \delta_3)(1 - \delta_4) \qquad (12)$$

and its value is: δ_{tot}=58 %.

The composition of the steel C80, determined using the optical emission spectrometer BAIRD DV6 type, is presented in Table 1.

The researches have been made, based on the singular drawing principle (one single pass through the die), using hardened wires, from D_0=3.50 mm to D_1=3.00 mm, classical drawing-CT and then, ultrasound drawing-UVD. There, also, have been used dies with metallic carbides cores, (WC), delivered by S.C. MECHEL Câmpia Turzii, with the half-angle of the cone $\alpha=8^0$; the lubrication has been made with stearates. The drawing process with and without ultrasounds, (UVD and CT), has been realized on the hydraulic wire-drawing bench of the experimental equipment BTL-01.000, 15 tf, type. The bench is properly equipped for the ultrasound drawing process-UVD. So, it has the ultrasounds generator IL10-2.0-0.1 type, 2000 W, with 22000 Hz resonant frequency and it works together with the magnetostrictor transducer equipped with a graded cylindrical concentrator made from a titanium alloy, in which, the die has been shrink on.

The ultrasound activation of the die has been made using oscillations with amplitudes having the following values: 15, 20 and 25 µm; so, based on the rel. (3), the vibratory rate of the die, $(\bar{v}_v)$ has had the following values: 2.07; 2.76 and 3.45 m/s.

The amplitude of the die oscillation has been measured with a device, especially realized for it, which has, as an active element, an electrets microphone (with capacitive functions), previously calibrated, [8]. The drawing force has been measured using the force cell CT-A-KN1C-type.

Table 1. Composition of the steel C80, mean values, [%].

C	Mn	Si	P	S	Cu	Cr	Ni	Al	N	As	Sn
0.82	0.52	0.20	0.09	0.014	0.01	0.04	0.01	0.03	0.026	0.001	0.001

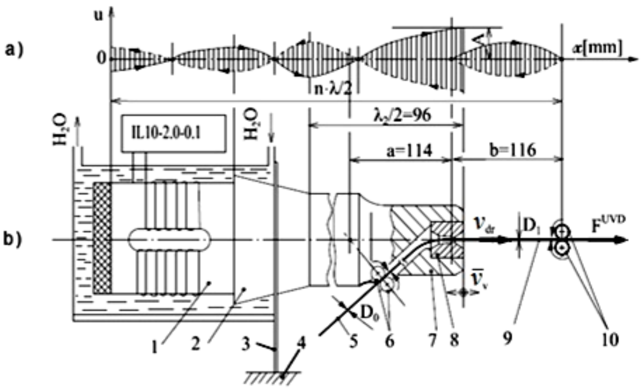

Fig. 5. Scheme of the oscillator system used for the research: a) waves oscillations; b) proper scheme:1-magnetostrictor transducer; 2-conical concentrator; 3-noduled flange; 4-hydraulic wire-drawing bench, BTL-01.000; 5- semi-finished wire; 6,10-ultrasonics energy reflectors (presser rolls): 7-graded cylindrical concentrator; 8-die; 9-drawn wire; — running wave; --- regressive wave.

Fig. 5 presents the scheme of the oscillator system used for the research dimensioned in $n \cdot \lambda/2$, (n-vertexes number; λ-wave length). Following smaller values of the temperature then the Curie one, the magnetostrictor transducer is water cooled, [3, 7].

The dimensioning of the oscillator system is based on the relation (13), [9]:

$$\lambda = c / f \qquad (13)$$

where: f=22.000 Hz – resonant frequency, c_{steel} =5050 m/s – ultrasounds wave velocity into the steel wire, $c_{titanium}$ =4260 m/s – ultrasounds wave velocity into the titanium.

So, considering the previously data, it results the length of the graded cylindrical concentrator $\lambda_2/2$=96 mm, for the wire $\lambda_1/2$=114 mm and the positioning distances of the ultrasonic energy reflectors:

$$a = \lambda_1 / 2 = 114 mm\,;$$

$$b = \lambda_1 / 2 + \left(D_o / D_1\right)^2 = 116 mm$$

The rate of drawing at the level of the wire-drawing bench BTL-01.000 type is 0.06 m/s.

Considering the diameter of the semi-finished wire D_0=3.50 mm and the diameter of the drawn wire D_1=3.00 mm, it results λ_i=1.36 and δ_i=19 %.

The lettering of the wires sets drawn by classical technology-CT and, respectively by ultrasounds technology-UVD is: A – classical technology-CT; B – ultrasounds technology-UVD, *A*=15 μm; C – ultrasounds technology-UVD, *A*=20 μm; D – ultrasounds technology-UVD, *A*=25 μm.

4. Experimental results

The influence of plastic deformation kinetics during the ultrasonics drawing-UVD of the cylindrical symmetry metallic wires in a hardened state, made of steel C80, takes into account the relative rate of drawing, $(v_{dr}/\bar{v}_v)$, with its influence on the resistance and on the plasticity mechanical characteristics, based on the results which have been obtained after the applying of the axial tension. The mechanical characteristics of resistance, R_m and $R_{p0.2}$, and of plasticity, A_{10}, researched on standard test pieces/EN 10002-1-1995, have been determined on the universal machine MTS 824.10 made in USA, with 20 mm/s the rate of stress and the analyzed values represent the arithmetic mean of the five tests.

The relative reductions of the drawing force, (ΔF), and of the mechanical characteristics of resistance, ΔR_m and $\Delta R_{p0.2}$, and of plasticity, ΔA_{10}, are given by the relations (14), [3,7]:

$$\begin{aligned}
\Delta F &= \frac{F^{CT} - F^{UVD}}{F^{CT}} \cdot 100\% \\
\Delta R_m &= \frac{R_m{}^{CT} - R_m{}^{UVD}}{R_m{}^{CT}} \cdot 100\% \\
\Delta R_{p0,2} &= \frac{R_{p0,2}{}^{CT} - R_{p0,2}{}^{UVD}}{R_{p0,2}{}^{CT}} \cdot 100\% \\
\Delta A_{10} &= \frac{A_{10}{}^{UVD} - A_{10}{}^{CT}}{A_{10}{}^{UVD}} \cdot 100\%
\end{aligned} \tag{14}$$

The obtained experimental results are shortly presented in Table 2 and Fig. 6, 7 and 8. The cumulative diagram after the applying of the axial tension for the four test pieces is presented in Fig. 6.

Fig. 7 presents the variation of the force parameters F^{CT} and F^{UVD}, as functions of the relative rate of drawing, $(v_{dr}/\bar{v}_v)$, during the drawing of the tyre cord made from steel C80.

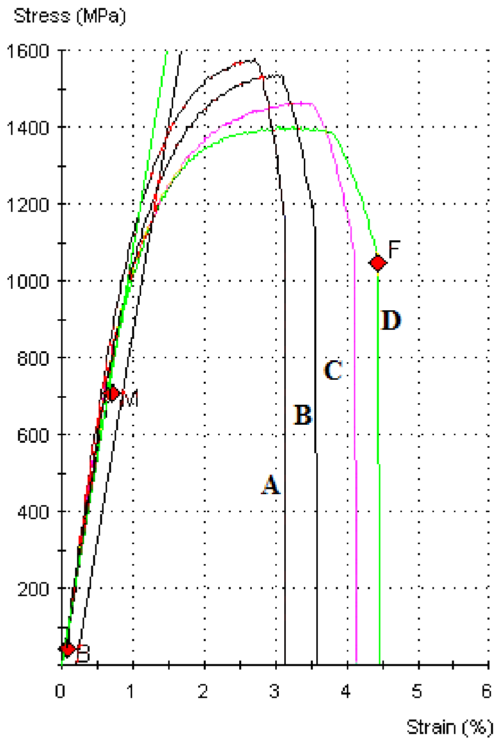

Fig. 6. Cumulative diagram after the applying of the axial tension for the four test pieces A, B, C and D.

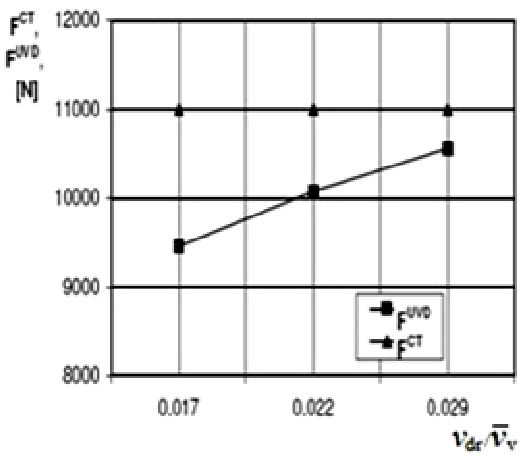

Fig. 7. Variation of the drawing force F^{CT} and F^{UVD}, depending on the relative rate of drawing, $(v_{dr}/\bar{v}_v)$.

Fig. 8 presents the variation of the relative reductions, ΔF, ΔR_m, $\Delta R_{p0.2}$, and ΔA_{10}, during the drawing of the steel tyre cord with and without ultrasounds, as functions of the relative rate of drawing, $(v_{dr}/\bar{v}_v)$.

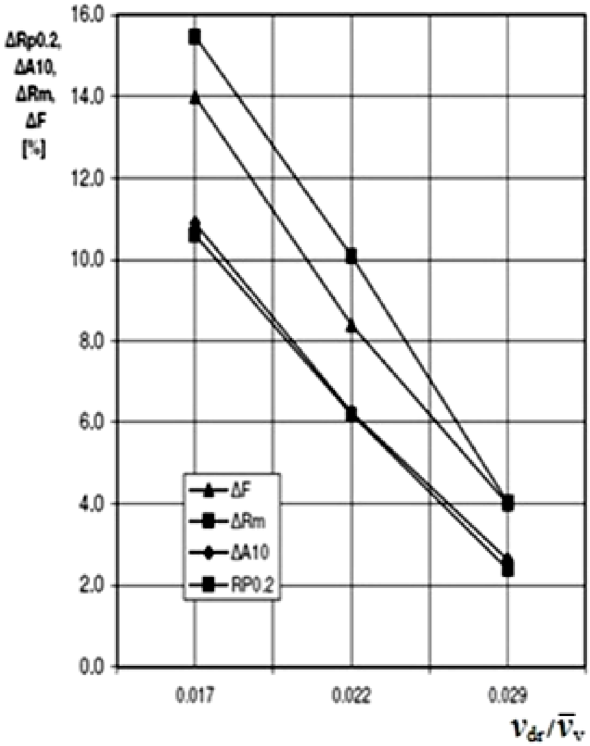

Fig. 8. Variation of the relative reductions, ΔF, ΔR_m, $\Delta R_{p0.2}$, and ΔA_{10} depending on the relative rate of drawing, $(v_{dr}/\bar{v}_v)$.

Table 2. Obtained experimental results, drawing CT and UVD process.

Symbol of the test piece	Drawing CT,UVD, D_0(3.50 mm) →D_1(3.00 mm)	$\frac{v_{dr}}{v_v}$ -	F^{CT} [N]	F^{UVD} [N]	R_m [MPa]	$R_{p0.2}$ [MPa]	A_{10} [%]	ΔF [%]	ΔR_m [%]	$\Delta R_{p0.2}$ [%]	ΔA_{10} [%]
A	CT	-	11000	-	1575	1485	3.49	-	-	-	-
B	UVD A=15 µm	0.029	-	10560	1535	1425	3.80	4.00	2.53	4.04	2.63
C	UVD A=20 µm	0.022	-	10075	1475	1356	4.01	8.40	6.34	10.10	6.25
D	UVD A=25 µm	0.017	-	9459	1405	1255	4.04	14.00	10.79	15.48	10.89

5. Conclusions

The paper represents a study about the influence of the plastic deformation kinetics, respectively, of the relative rate of drawing, $(v_{dr}/\bar{v}_v)$, on the force parameters and on the resistance and plasticity mechanical characteristics, during the ultrasonics drawing of the metallic wires with cylindrical symmetry, able to be hardened (steel tyre cord C80), when the die is placed in the maximum of the waves oscillations and it is activated along the drawing directions. So, an important influence is in the case of the decreasing of the relative rate of drawing value, $(v_{dr}/\bar{v}_v)$. Therefore, for $(v_{dr}/\bar{v}_v)$, it was obtained $\Delta F = 14\%$; $\Delta R_m \cong 11\%$; $\Delta R_{p0.2} = 15\%$ and $\Delta A_{10} = 11\%$. We consider these influences as a consequence of "the ultrasounds surface effect" or the reduction of the metal-tool contact friction effect, the measure of the mean friction reduction being the coefficient $\varphi, \varphi = f(v_{dr}/\bar{v}_v)$. In other words, it is possible to realize a technological control of the hardened effect, respectively, of the resistance and plasticity mechanical characteristics depending on the ratio $(v_{dr}/\bar{v}_v)$. The ratio $(v_{dr}/\bar{v}_v)$ is also very important in UVD technology because v_{dr} defines the technological efficiency and $\bar{v}_v$ gives enough information about the equipment which generates and transfers ultrasonics energy (see rel. (3)).

References

[1] E. Cazimirovici, M. Târcolea, I. Negulescu, D. Răducanu, Ed. Tehnică București, (1990).
[2] M. Susan, L. G. Bujoreanu, Revista de Metalurgia (Madrid) **35**(6), (1999).
[3] V. P. Severdenko, V. V. Klubovici, A. V. Stepanenko, Nauka i Tehnika, Minsk, (1996).
[4] M. Susan, L. G. Bujoreanu, D. G. Găluşcă, C. Munteanu, M. Mantu, J. Optoelectron. Adv. Mater. **7**(2), (2005).
[5] M. Susan, L. G. Bujoreanu, D. G. Găluşcă, C. Munteanu, V. Iliescu, Revista de Metalurgia (Madrid) **40**(2), (2004).
[6] Y. Daud, M. Lucas, K. R. Jamaludin, Journal of Applied Sciences **11**(9), (2011).
[7] B. Brown, I. E. Goodman, Hliffe Books, London, (2010).
[8] M. Susan, Ph.D. Thesis, Faculty of Materials Science and Engineering, “Gh. Asachi” Technical University Iasi, (1996).
[9] M. Susan, L. G. Bujoreanu, C. L. Dumitrache, L. C. Hanganu, C. Baciu, J. Optoelectron. Adv. Mater. **10**(6), (2008).
[10] B.-L. Gavrilă, M. Susan, V. Bulancea, Elena Chirilă, B. Cojocariu, O. Cristodulo, Proceedings of The 15th International Conference Mod Tech, Vol **1**, (2011).

*Corresponding author: chrlelena@yahoo.com