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THE ANALYSIS OF THE HIGH SPEED WIRE DRAWING PROCESS OF HIGH CARBON STEEL WIRES UNDER HYDRODYNAMIC LUBRICATION CONDITIONS

ANALIZA PROCESU CIĄGNIENIA Z DUŻYMI PRĘDKOŚCIAMI DRUTÓW ZE STALI WYSOKOWĘGLOWEJ W WARUNKACH SMAROWANIA HYDRODYNAMICZNEGO

In this work the analysis of the wire drawing process in hydrodynamic dies has been done. The drawing process of φ5.5 mm wire rod to the final wire of φ1.7 mm was conducted in 12 passes, in drawing speed range of 5-25 m/s. For final wires of φ1.7 mm the investigation of topography of wire surface, the amount of lubricant on the wire surface and the pressure of lubricant in hydrodynamic dies were determined. Additionally, in the work selected mechanical properties of the wires have been estimated.

It has been shown that in the drawing process under hydrodynamic lubrication by drawing speed of 25 m/s the phenomena of uncontrolled formation of the surface and the diameter of the wire appears, and in the process the compressive stresses eliminating cracks on the wire surface occur, causing further smoothing. The wires drawn hydrodynamically in speed of 25 m/s, besides clearly worse properties compared to the wires drawn hydrodynamically at speeds in the range of 5 to 20 m/s, also exhibit large dimensional variations.

Keywords: hydrodynamic dies, drawing speed, lubricant conditions, surface topography, lubricant pressure, mechanical properties

W pracy przeprowadzono analizę procesu ciągnienia drutów stalowych w ciągadłach hydrodynamicznych. Proces ciągnienia walcówki o średnicy 5,5 mm na druty o średnicy 1,70 mm zrealizowano w 12 ciągach, w zakresie prędkości 5-25 m/s. Dla drutów φ1,70 mm przeprowadzono badania topografii powierzchni, zmierzono ilość smaru na powierzchni drutów oraz określono ciśnienie smaru w ciągadłach hydrodynamicznych. Dodatkowo w pracy przedstawiono wybrane własności mechaniczne drutów.

Wykazano, że przy ciągnieniu w warunkach smarowania hydrodynamicznego z prędkościami rzędu 25 m/s występuje zjawisko niekontrolowanego kształtowania powierzchni i średnicy drutu, a występujące w tym procesie naprężenia ściskające eliminują pęknięcia powierzchniowe drutu, powodując jego dodatkowe wygładzenie. Druty ciągnione hydrodynamicznie z prędkością 25 m/s, oprócz zdecydowanie gorszych własności w porównaniu z drutami ciągnionymi hydrodynamicznie przy prędkościach w zakresie 5÷20 m/s, wykazują także duże odchyłki wymiarowe.

1. Introduction

Nowadays the main direction of the development of wire drawing mills is the implementation of the technology of high speed drawing process of high carbon steel wires. Based on current studies [1] it can be concluded that the high speed drawing causes intense heating of the surface of the wire, leading to the deterioration of lubrication conditions and properties of the drawn wires. This forces manufacturers to modifications of existing drawing technologies of high carbon steel wires.

One of the known ways of intensification of the drawing process and the improvement of properties of the steel wire is used in the drawing process of hydrodynamic lubrication, which creates conditions for the complete separation of the rubbing surfaces of the die and wire [2].

In order to achieve fluid friction, it is necessary to produce a layer of lubricant pressure exceeding a yield stress of the drawn metal [3-4]. Such conditions may be obtained either by hydrostatic or hydrodynamic. Hydrostatic lubrication is the method in which a pump lubricant under high pressure is supplied to the area of deformation [5]. However, due to the great difficulty of obtaining a sufficiently high lubricant pressure and the need for complicated seals of hydrostatic lubrication, the method has not found practical application in industry.

Another possible way to achieve in the drawing process the fluid friction is drawing in hydrodynamic lubrication conditions. Lubrication can occur at a certain critical speed depending on the dynamic coefficient of viscosity of the lubricant and the design of hydrodynamic die, also called in the literature as the die pressure [6].

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In the works by Avizur [7], Golis [8], Prajsnar [9], Sadok [10], Pilarczyk [5] and Łuksza [11] a positive effect of hydrodynamic lubrication on the properties drawn products has been demonstrated. Although the research presented in the literature for the most part focused on the drawing process with low speeds of the order of 1-7 m/s, and thus much lower than those currently used in wire plants, it is an important contribution to the explanation of the changes in hydrodynamic properties of drawn wires and delimits directions for further work on impact assessment of high speed hydrodynamic drawing process on properties of the steel wires.

The aim of this study is to analyze the phenomena occurring in the high speed multi-stage drawing process of high carbon wires in hydrodynamic dies and analysis of the impact of these phenomena on the formation properties of the wires after the drawing process.

2. Material and applied drawing technologies

The investigation of high speed multipass drawing process under hydrodynamic conditions has been performed for C78D high carbon steel wire (0.79% C). Before drawing, the wire rod was patented, itched and phosphated. The drawing process of φ5.5 mm wires in the final wire of φ1.7 mm was conducted in 12 passes, in industrial conditions, by means of a modern multi-die drawing machine Koch KGT 25/12, using hydrodynamic dies (Fig. 1) with an angle of drawing $2\alpha = 12°$. The drawing speeds in the last pass, depending on the variant of the drawing, was respectively: 5, 10, 15, 20, 25. Single reduction, G_p, and total reduction, G_c, are summarized in Table 1 while drawing speeds, v, are presented in Fig. 2.

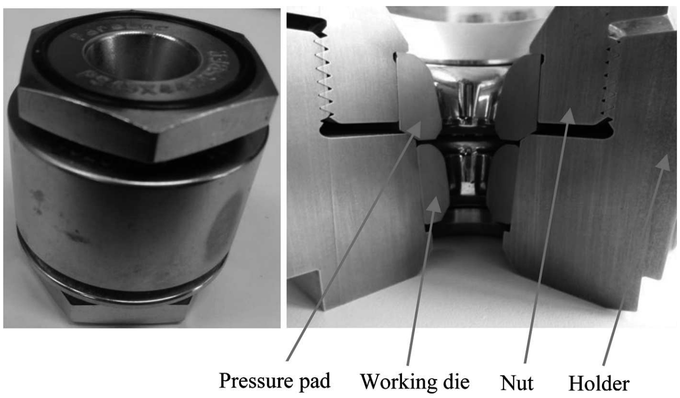

Fig. 1. Paramount hydrodynamic die TR4 type, casing B type

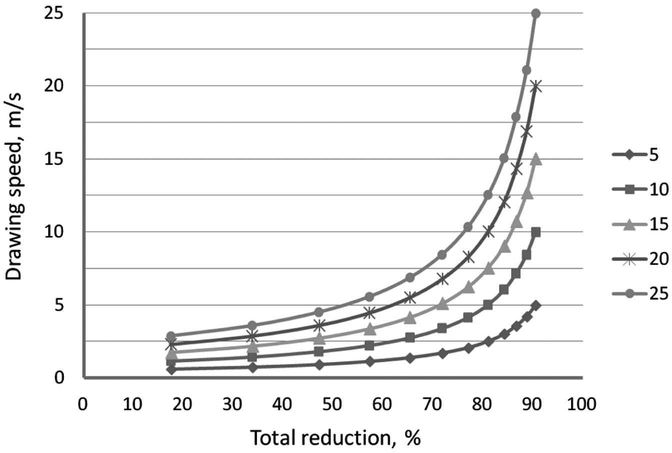

Fig. 2. Drawing speed in total reduction function

As a lubricant in the high speed multipass drawing process the next-generation multicomponent LUBRIFIL drawing powder has been applied, which is a mixture of different types of sodium soaps and inorganic additives. Additionally, in order to improve the lubrication of the first draft the rotating die (die speed was 15 rev/min) has been installed.

3. Analysis of lubrication conditions

The terms of friction on the contact surface of the wire and the die are one of the main factors influencing the state of the wire surface layer. In the high speed multi-stage drawing process the main physical parameters, which have significant impact on the wire surface layer, and thus the properties of drawn wire, are: friction, heat deformation, thermal lubricant resistance and its rheological properties. In the study presented in paper [12] it indicates that at high drawing speeds, especially in the case of a conventional drawing, there is a very short intense heating of the surface of the wire, which significantly contributes to the deterioration of lubrication conditions in the drawing process. The use of hydrodynamic dies, makes it possible to reduce the friction in the drawing process, thus contributing to the drop in temperature of wires. It should have a positive impact on the lubrication conditions in the drawing process.

TABLE 1

Distribution of single reduction G_p and total reduction G_c

Draft	0	1	2	3	4	5	6	7	8	9	10	11	12
φ, mm	5.50	5.00	4.48	4.00	3.60	3.24	2.92	2.64	2.40	2.19	2.01	1.85	1.70
G_p, %	-	17,.4	19.7	20.3	19.0	19.0	18.8	18.3	17.4	16.7	15.8	15.3	15.6
G_c, %	-	17.4	33.7	47.1	57.2	65.3	71.8	77.0	81.0	84.2	86.6	88.7	90.5

In order to establish the effect of high drawing speed in hydrodynamic dies on lubrication conditions the amount of lubricant on the surface of final $\varphi 1.7$ mm wires was estimated. The results are presented in Fig. 3.

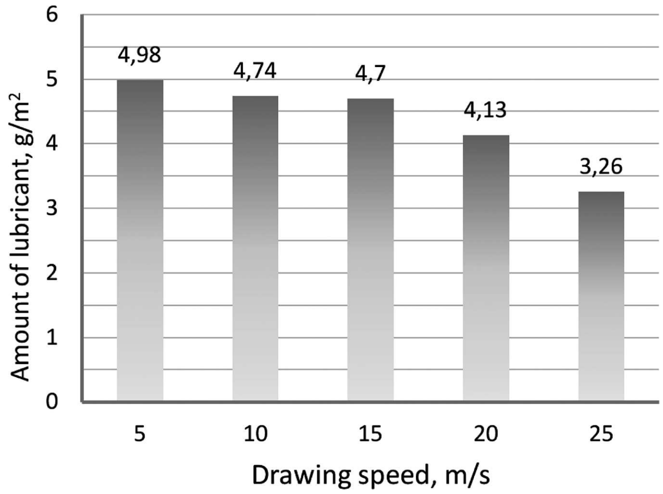

Fig. 3. The influence of drawing speed on the amount of lubricant on the surface of final $\varphi 1.7$ mm wires drawn in hydrodynamic dies

Test results presented in Fig.3 show that the use of hydrodynamic dies at high speed drawing process significantly improves lubrication. Differences in the amount of lubricant on the wire drawn of 5 to 20 m/s are negligible. Further increasing the drawing speed causes only a gradual deterioration of lubrication. For the wire drawn at the speed of 25 m/s, relative to the wires drawn at a speed of 5 m/s, there was a decrease of 34% of lubricant. However, on the wire surface drawn at the speed of 25 m/s there is still enough thick lubricant carrier to provide the hydrodynamic effect.

4. Analysis of surface topography of drawn wires

Lubrication conditions in the drawing process significantly affect the surface roughness of wires. Therefore, in the work the effect of high drawing speed on the surface topography of the 1,7φ mm wires drawn in hydrodynamic dies has been assessed.

The analysis of the geometric structure of the surface of the wires can be done based on a traditional 2D surface roughness measurement and based on a three-dimensional (spatial) surface analysis. Analysis of surface topography in terms of 3D allows to specify not only the parameters of the elevation and longitudinal surface features, but also the shape parameters of inequality and anisotropy of the surface [13].

3D surface topography studies were performed using From Talysurf Profilometer by Rank Taylor Hobson and the results were obtained with using software developed by TalyMap Platinum. The surface of the samples with dimensions of 0.55 mm×1 mm in a transverse direction to the direction of drawing were analyzed.

To illustrate the surface topography changes by drawing wires at high speeds, the following parameters has been selected:

– amplitude parameters, ie roughness St (the distance between the highest and the lowest point of the surface), ten-point height of irregularities surface Sz (average absolute height of the five highest and five lowest vertex cavities), arithmetic mean surface roughness Sa, root mean square roughness Sq;

– the spatial parameters, namely: the ratio of surface texture Str (this parameter ranges from 0 to 1, with values close to 1 indicate a geometric structure surface with a high level of isotropy).

Fig. 4 presents the surface topography of the wire of $\varphi 1{,}7$ mm drawn at a speed of 25 m/s, whereas in Fig. 5-6 there are graphs illustrating the effect of drawing speed on selected parameters of the geometric structure of the wire surface.

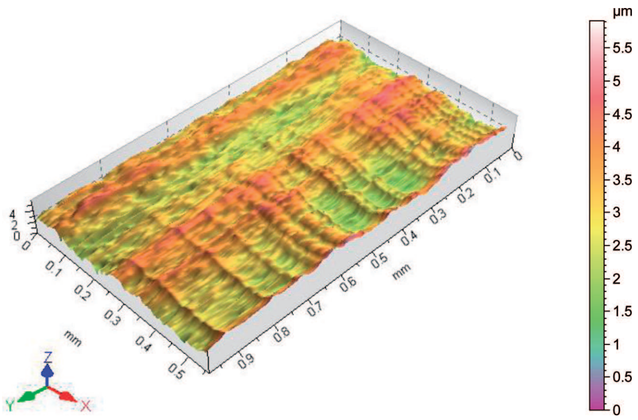

Fig. 4. The surface topography of the wire drawn in hydrodynamic dies with drawing speed v=25 m/s

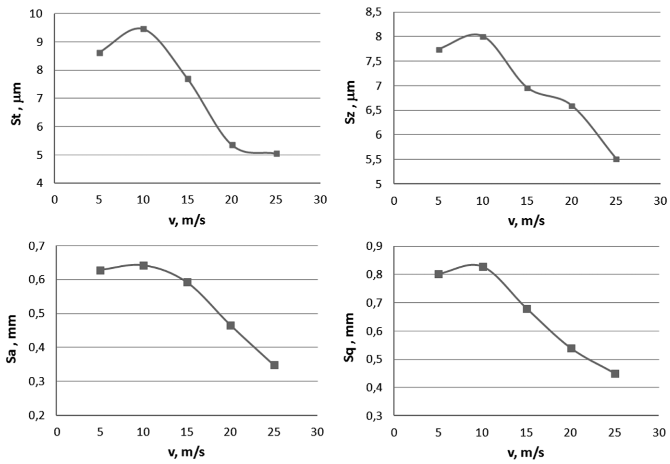

Fig. 5. Effect of the drawing speed on surface amplitude parameters of the 1.7 mm final wires

By analyzing the surface topography of drawn wires, it can be concluded that after the drawing process the surface configuration is characterized by a random anisotropy and the amount of directing the geometrical structure of the surface depends on the speed of the drawing, as evidenced by the work described in the parameter Str, Fig 6.

Analysis of the changes in the topography of the wires drawn in hydrodynamic dies, Fig. 5, demonstrated that the formation of the surface by drawing the liquid friction conditions are much more complex than those found in conventional method of drawing. In method of hydrodynamic drawing amount of lubricant supplied under pressure between the friction surfaces of the wire and the die is much greater than in a conventional drawing, which creates the conditions for the complete separation of the rubbing surfaces and wire drawing dies. A thick layer of lubricant and high pressure make it possible to determine freely the wire surface, which may lead to the rise and decline of surface roughness.

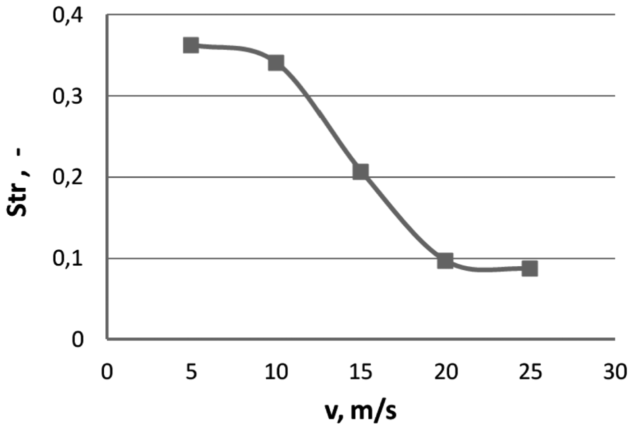

Fig. 6. Effect of the drawing speed on surface spatial parameter Str of the 1.7 mm final wires

Studies suggest also that in speed range 5-10 m/s factor determining the surface roughness of drawn wires in hydrodynamic dies is the amount of lubricant on the wires, but at speeds above 10 m/s the factor contributing in a decisive way to the topography of the surface is lubricant pressure. From the theory of hydrodynamic drawing that at similar values of the coefficient of dynamic viscosity the lubricant pressure increases with increasing drawing speed. At drawing speeds exceeding 10 m/s lubricant pressure caused only a slight deformation of the vertices, and a thick layer of lubricant prevented their shear, hence the drawn wires with a speed of 10 m/s had the highest values of roughness parameters.

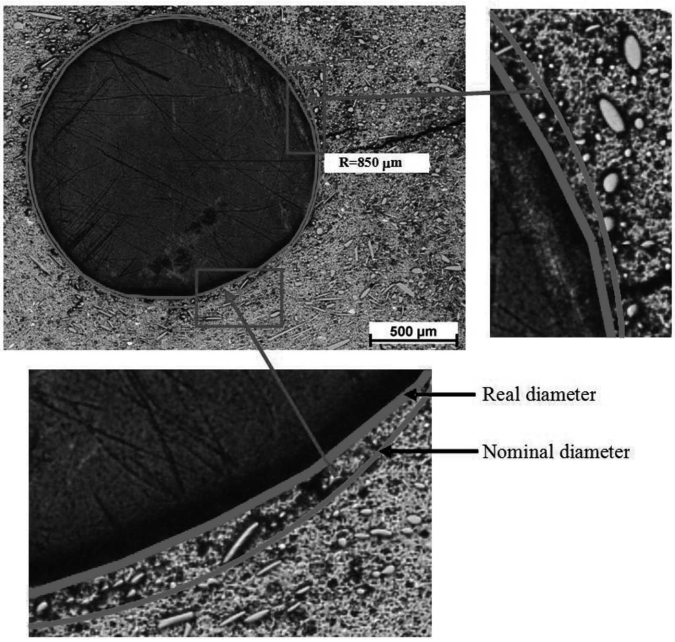

Fig. 7. Cross-section of the φ1,7 mm final wire drawn in hydrodynamic dies (drawing speed v = 25 m/s)

However, at higher drawing speeds definitely more important factors influencing the roughness parameters are layers of lubricant, ie. pressure and adhesion. At the drawing speed of 25 m/s the very high lubricant pressure caused phenomena of uncontrolled formation of the surface and the diameter of the wire, and the compressive stresses that occur in the process, eliminating cracks on the wire surface, cause further smoothing.

The phenomenon of uncontrolled shaping of the diameter of the wire in the hydrodynamic process confirmed by Fig. 7 which shows that the wire drawn in hydrodynamic dies at speed of 25 m/s can exhibit dimensional variations, and its cross section may have a slight waviness.

5. The estimation of the lubricant pressure in hydrodynamic dies

Drawing in the hydrodynamic lubrication conditions occurs when the pressure of lubricant in the hydrodynamic die exceeds the yield strength of a drawn wire and created the lubricant film completely separates the friction surfaces of the wire and the die. In fact, under both laboratory and industrial thick layers of lubricant generally do not cover all edge roughness, thus with an increase in the total reduction the roughness of the wire decreases. The analysis of the literature shows that with the drawing speeds of less than 2 m/s it is very difficult to obtain high pressure in the die, and calculations performed have shown that the pressure does not usually exceed 300 MPa and is much lower than the yield stress of the steel. Too little lubricant pressure, lower than the yield strength of drawn wire, does not provide the full effect of hydrodynamic, but allows the occurrence of pseudohydrodynamic friction, occupying the intermediate space between the hydrodynamic friction and the border. Thus, according to Wistreich, in most cases, the application in the drawing process the hydrodynamic dies, allows usually to obtain pseudohydrodynamic effect [2].

In order to demonstrate the hydrodynamic effect in high speed of multi-stage wire drawing process it is necessary to estimate the lubricant pressure. For the correct application of the lubricant pressure in the hydrodynamic drawing process it is necessary to know the dynamic coefficient of viscosity of the lubricant.

The literature suggests that the viscosity coefficient of sodium soap is typically in the range of 100 to 200 Pa·s [14]. This was performed by viscosimetric method and the results were verified experimentally. To determine the lubricant pressure in the resistance die (also called as pressure sleeve) the model developed by Golis and co-workers was used [15]:

$$p = \frac{6 \cdot \eta \cdot v \cdot L}{h_0 \cdot h}, \text{ MPa} \tag{1}$$

where:

v – drawing speed, v = 5-25 m/s,

L – length of pressure pad , $L = l + l_c$, for last draft L = 6.25 mm,

h_0, h – the slit respectively, the input and output resistance of the die, for the last draft

h_0 = 0.825 mm, h = 0.075 mm,

η – dynamic viscosity coefficient, η = 50-250 Pa·s.

The presented above geometrical parameters of the die resistance were measured on a profilometer in the laboratory plant for the production and regeneration of the dies, which can provide high accuracy measurement. The results showing the effect of drawing speed and the coefficient of dynamic viscosity of the lubricant at a constant pressure of parameters measured resistance of the die are shown in Fig. 8.

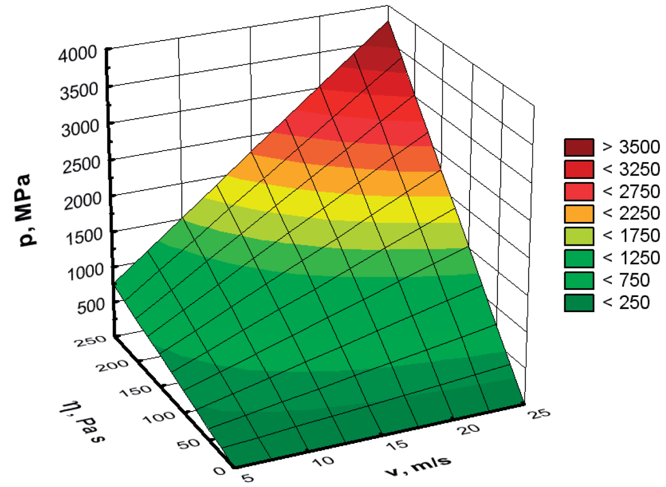

Fig. 8. Plane showing the change in lubricant pressure p as a function of drawing speed v and the coefficient of dynamic viscosity η

The data presented in Fig. 8 shows that the lubricant pressure in the hydrodynamic drawing process at a constant of the resistance die parameters is dependent on the product of the drawing speed and the dynamic coefficient of viscosity. At the coefficient of viscosity η =const the lubricant pressure increases in proportion to the drawing speed. Hence, when η =200 Pa·s five-fold increase drawing speed of 5 to 25 m/s caused an increase in lubricant pressure from 606 to over 3000 MPa. This would imply that at v=25 m/s at the outlet of the pressure sleeve occurs plastify of the wire. However, when the draw speed less than 10 m/s the increase of lubricant pressure in the die resistance is too small to obtain the full hydrodynamic effect. However, it should be remembered that the output wire of the die resistance (pressure sleeve) is a further increase in lubricant pressure, which reaches its maximum value at the interface of the approach angle of the die working. According to the author, at low drawing speeds lubricant pressure large enough for the plastic deformation of the wire occurs only in the vicinity of the zone of deformation.

It has been found that at high speed drawing process the increase of lubricant pressure in the resistance die and approach angle of the die caused the high pressure substantially in excess of the yield stress of the wire. Thus, wires drawn at speed of 25 m/s exhibit dimensional deviations, and its cross section is characterized by a waviness (Fig. 7). Reducing the diameter of the wire and the circumferential waviness demonstrate substantial fluctuations in lubricant pressure in the pressure chamber. The results are consistent with the work of [16], in which the authors dimensional deviations drawn wire in dies hydrodynamic perceive in too much pressure.

6. Mechanical properties

Presented above studies have shown that at high drawing speeds, a result of a high lubricant pressure occurs in the hydrodynamic die uncontrollably forming wire surface, which certainly should affect its properties. Hence, the paper presents mechanical properties of drawn wires, Fig. 9.

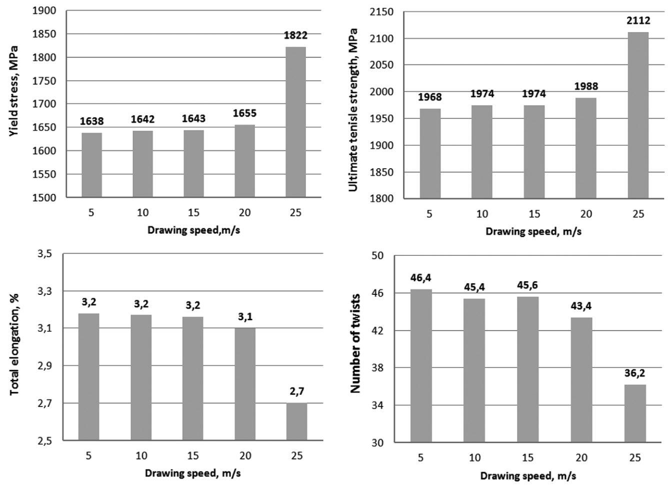

Fig. 9. Effect of drawing speed on the mechanical properties of the φ1,7 mm final wires

Mechanical investigations confirmed that too high increase of the pressure in the hydrodynamic die at high speeds of 25 m/s, resulted in further deformation of the wire and an increase in its strength properties, the deterioration of plastic properties and a decrease in the number of twists. Undoubtedly, the rapid decline in the number of twists in the wires drawn at a speed of 25 m/s to be associated with higher strength properties, inferior plastic properties and a more heterogeneous strengthening the surface layer of wire, caused by the impact of high lubricant pressure in the die during the drawing process.

The real diameter of the final wires drawn hydrodynamically at a speed of 25 m/s oscillated in ranged from 1.60-1.66 mm. However, when drawing speeds not exceed 20 m/s, there were no deviations. Thus, at the same final wire diameter of 1.7 mm and a very good lubrication conditions the increase of the drawing speed of 5 to 20 m/s did not affect significantly on the mechanical properties of the wires. Therefore, it is expected that a suitable modification of the hydrodynamic die allows the drop of lubricant pressure in the die, at drawing speeds of the order of 25-30 m/s, it should be possible to obtain after drawing process the wires, the dimensional deviations do not exceed the industry standards and mechanical properties are similar to those obtained for wires drawn at 5-20 m/s.

7. Conclusion

From the experimental tests carried out, the following findings and conclusions are drawn:

1. The industrial trial of high speed drawing process of high carbon steel wires showed that the use of hydrodynamic dies phosphate lubricant carries, as well as a new generation of multi sodium lubricants, significantly improves the lubrication conditions and enables the hydrodynamic effects at speeds exceeding 20 m/s.
2. It has been proved that the wire topography in the drawing process is characterized by a random anisotropy and

the amount of directing the geometrical structure of the surface depends on the drawing speed.

3. It has been found that with drawing in hydrodynamic dies a thick layer of lubrication and high pressure makes it possible to shape freely the wire surface, which may lead to both an increase and decrease of surface roughness.
4. Too high increase of lubricant pressure in the pressure sleeve and die cone work input in the high speed hydrodynamic drawing process can lead to fluctuations in the pressure of lubricant and uncontrolled formation of the wire surface. The wires drawn hydrodynamically at a speed of 25 m/s, in addition to far inferior properties compared with wires drawn hydrodynamically at speeds in the range of 5 to 20 m/s, also exhibit large dimensional variations.
5. The results obtained in the work of theoretical and experimental research can be used in the design of wire drawing technology of carbon steel at high speeds and enable them to improve the quality of their wires and intensify their production processes.

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