Arch. Metall. Mater. **64** (2019), 4, 1353-1359

DOI: 10.24425/amm.2019.130101

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THE EFFECT OF THE LENGTH OF THE DRAWING DIE SIZING PORTION ON THE ENERGY AND FORCE PARAMETERS OF THE MEDIUM-CARBON STEEL WIRE DRAWING PROCESS

The paper discusses a theoretical and an experimental analyses of steel wire drawing in conical drawing dies with a varying length of the die sizing portion. The theoretical analysis was performed in the Drawing 2D, where the wire temperature and drawing stress were determined. The theoretical study was verified by the measurement of drawing force under laboratory conditions and by industrial multi-stage drawing tests carried out under commercial conditions. A relationship has been shown to exist between die sizing portion length and wire temperature and drawing stress.

Keywords: conical die, wire drawing, temperature, drawing stress

1. Introduction

The development of plastic working entails an increasingly better steel wire manufacturing technology. New-generation wire production machinery enable now new, more effective high-speed drawing technologies to be implemented in wire drawing plants. Literature reports [1] show that in drawing at high speeds, intensive heating of the top wire layer occurs, which leads to a change in friction conditions.

One of the main factors influencing the drawing process is drawing die geometry [2-5]. Among the most commonly used drawing dies are conventional conical dies. The main parameters describing a drawing die include the drawing angle is the length of the drawing die sizing portion. Some information on the effect of drawing die geometry on the drawing process and wire properties can be found in the literature, but in the majority of cases those references are related to laboratory tests only. Industrial tests carried out by the author have shown that in the multi-stage drawing process, as a result of a high temperature occurring at the contact between the wire and the die, varying lubrication and friction exist in individual draws, which poses difficulty in selecting the optimal drawing die geometry.

In the drawing process, the magnitudes of drawing stress and wire temperature depend on the work necessary for plastic deformation and the work needed to overcome the friction forces.

In many works it has been shown [1,6-7] that in the drawing process the decisive factor for the high surface temperature of the wire is the heat generated as a result of friction, which leads to an increase in the temperature mainly of the surface layer of the wire. With the increase of the drawing speed, the thickness of the wire layer heated by the friction decreases. With a drawing speed of 20 m/s, the thickness of this layer is below 100 μm. This leads to additional accumulation of heat and temperature increase, which may exceed 1000C°. Therefore, it is reasonable to optimize tools to reduce friction forces in the dies. Few literature data [8-12] indicate that when drawing steel wires, the length of the calibrating part of the die can affect the heating of the wire and the drawing stress. Unfortunately, these tests relate to laboratory conditions, at drawing speeds below 2 m/s, significantly differing from those occurring in real industrial drawing processes. There are no studies in the literature regarding the influence of the length of the calibration part of the die on the energy-force parameters of the process of drawing multi-stage steel wires.

In the authors' view, the selection of the appropriate die sizing portion length may contribute to a reduction of the friction forces in the die, which is expected to reduce the wire temperature and drawing stress and to improve the lubrication conditions in the process of drawing steel wire. A theoretical and an experimental analyses of the process of drawing steel wire in conical drawing dies with a varying length of the die sizing portion have been made within the study.

2. Material and technology

The test material was 5.5 mm-diameter wire rod of medium-carbon steel, which was drawn in seven drafts under commercial conditions into wire of a diameter of 2.2 mm at a drawing speed

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TABLE 1

Chemical composes of steel

C	Mn	Si	P	S	Cr	Ni	Cu	Al	N	Fe
0.400	0.640	0.188	0.012	0.011	0.030	0.007	0.030	0.004	0.005	Remaining

TABLE 2

The distribution of sinle drafts G_p, total draft G_c and drawing speed v

Draft	0	1	2	3	4	5	6	7
ϕ, mm	5.50	4.73	4.10	3.57	3.13	2.77	2.46	2.20
G_p, %	—	26.04	24.86	24.18	23.13	21.68	21.13	20.02
G_c, %	—	26.04	44.43	57.87	67.61	74.64	79.99	84.00
v, m/s	—	2.12	2.86	3.80	4.94	6.31	8.00	10.00

of 10 m/s (Table 1-2). The drawing process was conducted in conical dies of an angle of $2\alpha = 12°$. At the last drawing draft, die sizing portion length, l, was as follows, respectively: 0.2; 0.4; 0.60; 0.8 and 1d, where $d = 2.2$ mm.

3. Theoretical analysis of the drawing process

The theoretical analysis of the multi-stage drawing process was made based on the Drawing 2D program [13]. Simulation of the multi-stage drawing process was carried out for wire with the plastic properties of steel C40, as taken from the Drawing 2D program's database.

The wire drawing process was assumed to proceed in conventional dies with an angle of $2\alpha = 12°$ with reduction and at drawing speeds, as given in Table 2. The initial temperature of the wire prior to entry to the first and subsequent dies was 20°C.

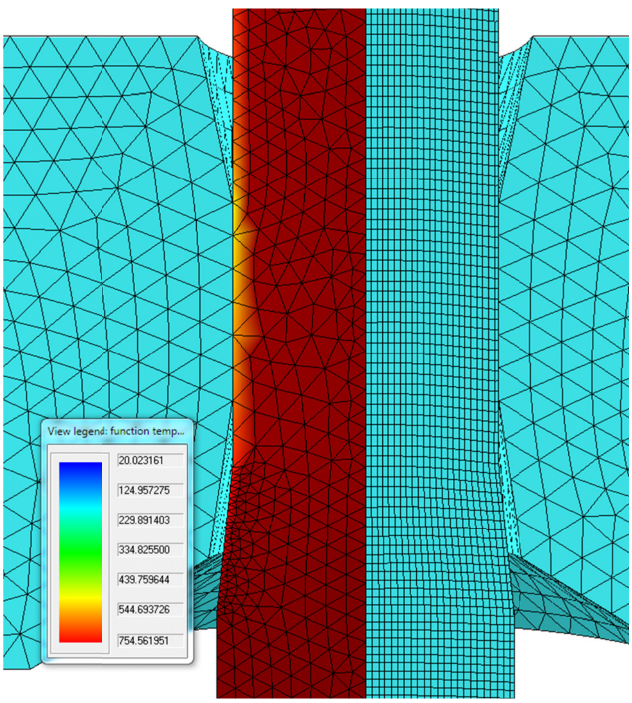

Fig. 1. Distribution of temperature during drawing of wire from the diameter of 2.46 to a diameter of 2.2 mm with a die sizing portion length of $l = 1d = 2.2$ mm

The average friction coefficient assumed in modelling was the same for all draws, amounting to $\mu = 0.07$.

To determine the effect of die sizing portion length on wire heating up, the values of wire surface temperature T_s were red out from grid nodes located at wire exit from the die sizing portion. Figure 1 shows an example of temperature distribution during drawing wire from ϕ2.46 to ϕ2.2 mm.

The temperature and drawing stress in the last draw were determined. Figure 2 illustrates the effect of die sizing portion length on the wire surface temperature, T_s, while average wire temperature, T_{av}, is depicted in Figure 3.

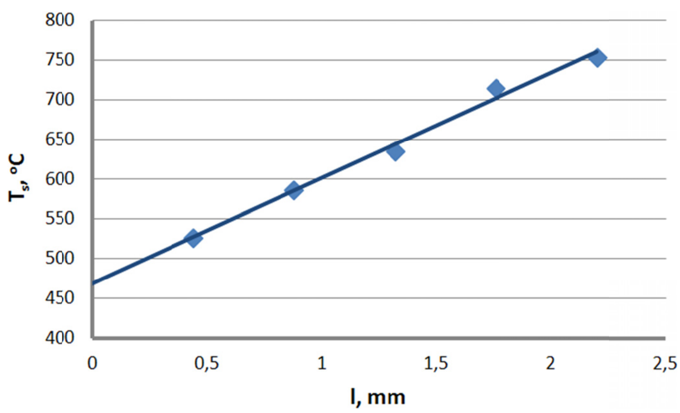

Fig. 2. Variation in wire surface temperature T_s as a function of die sizing portion length l (drawing from ϕ2.46 to ϕ2.20 mm)

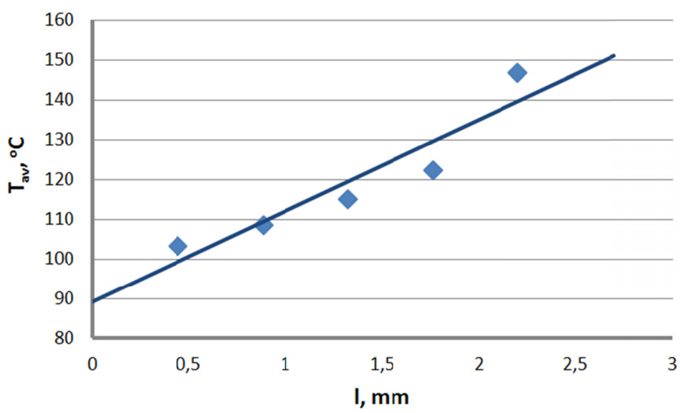

Fig. 3. Variation in average wire temperature T_{av} as a function of die sizing portion length l (drawing from ϕ2.46 to ϕ2.20 mm)

The tests showed that intensive wire heating up in the die sizing portion occurred in the multi-stage drawing process, whereas, the larger the die sizing portion length, the higher the wire surface temperature. Increasing the die sizing portion length from 0.2d to 1d resulted in an increase in wire surface temperature by 43.3% and an increase in average temperature by 41.9%. The higher temperature values for wires drawn in dies with a longer die sizing portion can be related to an increase in friction forces at the wire-to-die contact, which cause the wire to heat up on the die surface, with the simultaneous transfer of heat by conduction to the wire axis. The increase in friction forces causes not only an increase in wire temperature, but also an increase in drawing stress. This is confirmed by the simulation results illustrated in Figure 4.

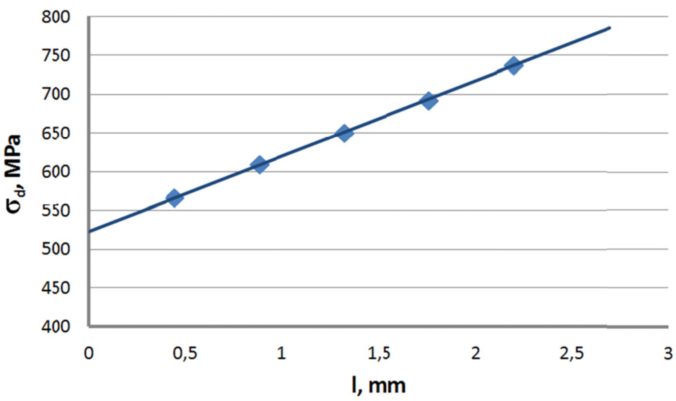

Fig. 4. Variation in drawing stress σ_d as a function of die sizing portion length l (drawing from ϕ2.46 to ϕ2.20 mm – simulation)

To make a more complete analysis of the effect of die geometry on the force parameters of the drawing process, theoretical calculations of the drawing stress were also performed within the study. There are a number of empirical formulas available in the literature, which enable the estimation of the drawing stress [6]. The most commonly formulas include Tarnawski's formula (1):

$$\sigma_d = \frac{K_{av}}{1+\frac{2\mu l}{R}}\left[\frac{2\mu l}{R} + q + (1+ac)\ln\lambda + cD\right] \quad (1)$$

$$D = 1.6\left(\sin\alpha\sqrt{\mathrm{tg}\alpha} + \mu^2\sqrt{\mathrm{ctg}\alpha}\right)\sqrt{\ln\lambda}$$

$$q = \frac{\sigma_0}{K_{av}}$$

$$c = 1 - q$$

$$a = \mu \cdot \mathrm{ctg}\alpha$$

K_{av} – average value of deformation resistance, $K_{av} = 1250$ MPa

σ_0 – back tension, MPa

μ – friction coefficient, $\mu = 0.07$

l – die sizing portion length, $l = 0.2 - 1d = 0.44 - 2.2$ mm

λ – elongation factor, $\lambda = 1.25$

R – wire radius after drawing, $R = 1.1$ mm

α – die angle, $\alpha = 5°$.

The calculation of the drawing stress was made for the last draw. Wire was assumed to be drawn from the diameter of 2.46 mm to a diameter of 2.2 mm with the length of the die sizing portion ranging from 0.44 to 2.2 mm and with a constant deformation resistance value, independent of the die length l. The calculation results are illustrated in Figure 5.

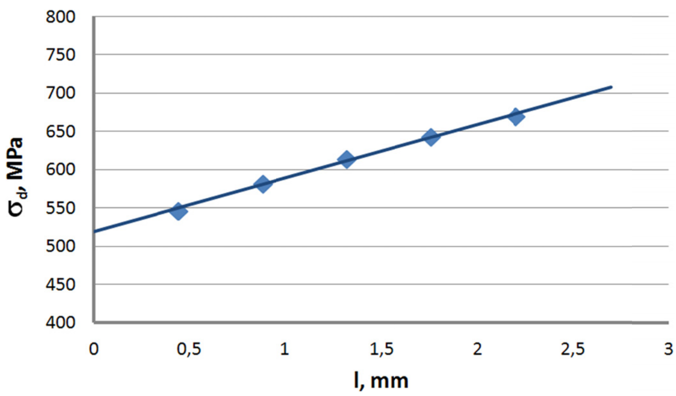

Fig. 5. Variation in drawing stress s_d as a function of die sizing portion length l (drawing from ϕ2.46 to ϕ2.20 mm – Tarnawski's formula)

In the drawing process, drawing stress is the sum of plastic deformation resistances and the work of friction forces in the die approach portion and the work of friction forces in the die sizing portion. Figures 4-5 clearly show that with the increase in die sizing portion length, the drawing stress increases. The differences in obtained stress values between wires drawn in dies with a length of $l = 0.2d$ and $1 = 1d$ amounted to, respectively, 30.3% for simulation and 22.5% for Tarnawski's formula. So, using the shortest possible die sizing portion length should favourably influence the force parameters of the drawing process, lower the risk of wire rupture during the drawing process and reduce the energy consumption.

In wire drawing practice, the length of the die sizing portion depends on many factors, including steel grade, surface treatment type, drawing method, the distribution of single reductions and the total reduction, drawing speed, drawing speed and drawing designation. Die sizing portion length normally ranges from 0.4 and $1d$, whereas, the smaller the wire diameter, the larger the percentage of the die sizing portion length. It should be borne in mind that too small a die sizing portion length may significantly accelerate the die wear. On the other hand, however, drawing wire in the diameter range of 2-5 mm in dies with a large sizing portion length of $l = 1d$ results in a significant increase in friction, which will lead to wire surface grinding and a marked increase in drawing stress. The process of multi-stage drawing at high speeds of around 25 m/s, using dies with a longer sizing portion causes an instability of the drawing process and a rupture of the wire in the die. In the author's view, the optimal die sizing portion length in the diameter range of 2-5 mm is a length of $l = 0.3d$.

The theoretical analysis of the drawing process does not cover all phenomena occurring during the process of drawing steel wires, while computer simulations are, in a sense, a simplified model. Therefore, to confirm the effect of die sizing portion length on the energy and force parameters of the drawing process, the verification of the theoretical examination results was made within the study.

4. Verification of the theoretical examination of the drawing process

The verification of the theoretical examination of the drawing process included the industrial measurements of drawn wire temperature and the measurement of the percentage motor load in the last draft. These were complemented with the measurement of drawing stress for the last draft in laboratory conditions.

In the process of multi-stage drawing, the measurement of wire temperature is a complex matter. At drawing speeds of up to 25 m/s, the speed of wire reeling and unreeling is about 80 km/h. After wire has been wound onto a drawing drum, a rapid drop in its temperature takes place by convection, radiation and conduction, so the temperature of the wire exiting the drum to be fed to the next draw normally does not exceed 100°C. Additionally, at so high speeds, wire vibrates as it is drawn, which makes the temperature measurement of a single wire impossible. Therefore, an attempt was made in the study to take a wire temperature measurement on the drawing drum. Wire temperature was measured with a pyrometer, while the measured temperature values should be treated as the average temperature of partially cooled wire. The measurement results are shown in Figure 6.

The industrial wire temperature measurement tests confirmed the theoretical examination of the drawing process. The data in Figure 6 shows that the length of the die sizing portion in the multi-stage drawing process has a significant effect on wire heating up. With increasing die sizing portion length, the wire temperature increases. Using drawing dies with a large sizing portion length of $l = 1d$ resulted in an increase in average drum wire temperature by 30%, compared to wires drawn in dies with $l = 0.2d$. Industrial tests carried out by the author [1] have unquestionably shown that the increase in wire temperature during multi-stage drawing impairs the lubrication conditions.

Drawing lubricants used industrially have limited thermal resistance. The increase in temperature on the wire/die contact surface causes a decrease in lubricant viscosity and, in extreme cases, even a thermal decomposition of the lubricant. In the wire

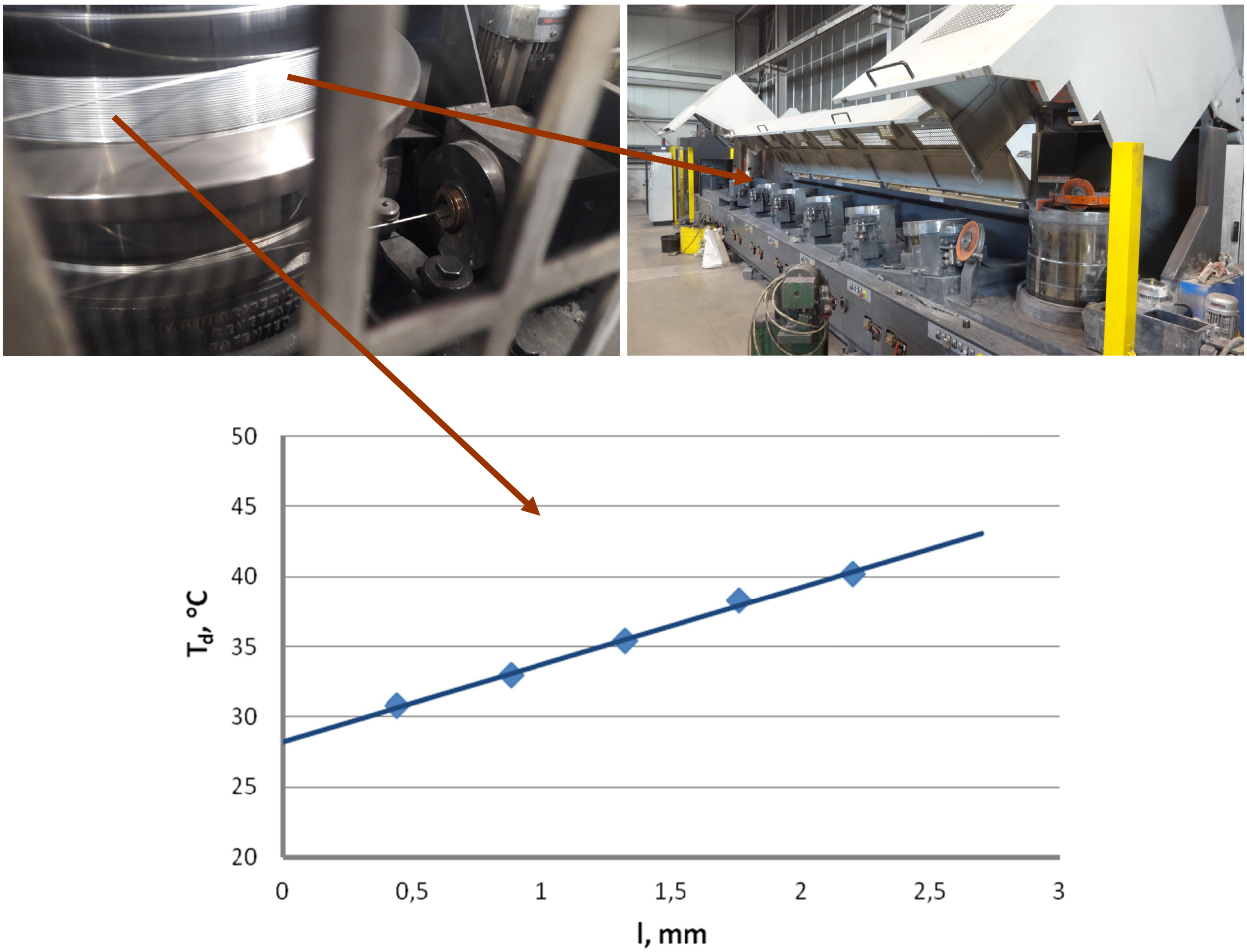

Fig. 6. The temperature of wire cooled down on the drawing drum T_d as a function of die sizing portion length l (drawing of wire under industrial conditions from ϕ2.46 to ϕ2.20 mm at a speed of 10 m/s)

drawing process, the wire temperature increases proportionally to the drawing speed. Increasing the drawing speed by a factor of five results in an about twofold increase in wire surface temperature. The speed of drawing medium- and high-carbon steel wires normally does not exceed 20 m/s. So, the additional temperature increase in dies with a long sizing portion causes additional heating up and markedly limits the intensification of the drawing process. The increase in friction forces in drawing dies with $l = 1d$ causes also an increase in drawing resistance, as confirmed by the industrial measurements of drawing machine's motor load. Modern multi-stage drawing machines enable the recording of a series of drawing process parameters, including the percentage load of individual drawing machine motors. Figure 7 represents the percentage variation of motor load as a function of die sizing portion length *l*.

From the data in Figure 7 it can be found that with increasing die sizing portion length the percentage load of drawing machine motors increases. The differences between the examined variants amounted to 7.3%. The higher motor load for drawing variants using dies with an increased die sizing portion length should be associated with a greater drawing stress. Industrial verification based on the measurement of drawing machine motor load cannot be explicitly translated to the drawing force magnitude. Nevertheless, these tests have conclusively established that, in an actual drawing process, decreasing the length of the die sizing portion reduces the drawing resistance and enhances the stability of the drawing process.

As the industrial tests allowed only the estimation of the percentage motor load, an attempt was made in the study to determine the drawing forces and stresses under laboratory conditions. To this end, 2.46 mm-diameter wire was drawn into a diameter of 2.2 mm at a drawing speed of v = 0.03 m/s with the use of a testing machine, using a varying die sizing portion length. Drawing tests conducted at such low drawing speeds do not fully reflect the real conditions of multi-stage drawing and do not allow for the effect of wire heating up on the lubrication conditions. Nevertheless, these tests enable a precise measurement of the drawing force, with an accuracy much higher than possible by reading out force parameters from the drawing machine's control panel. The test results are shown in Figure 8-9.

The laboratory measurement of the drawing force performed within the study confirmed that increasing the die sizing portion length from $l = 0.2d$ to $l = 1d$ resulted in an increase in drawing force by 10.8%, and the obtained results only slightly

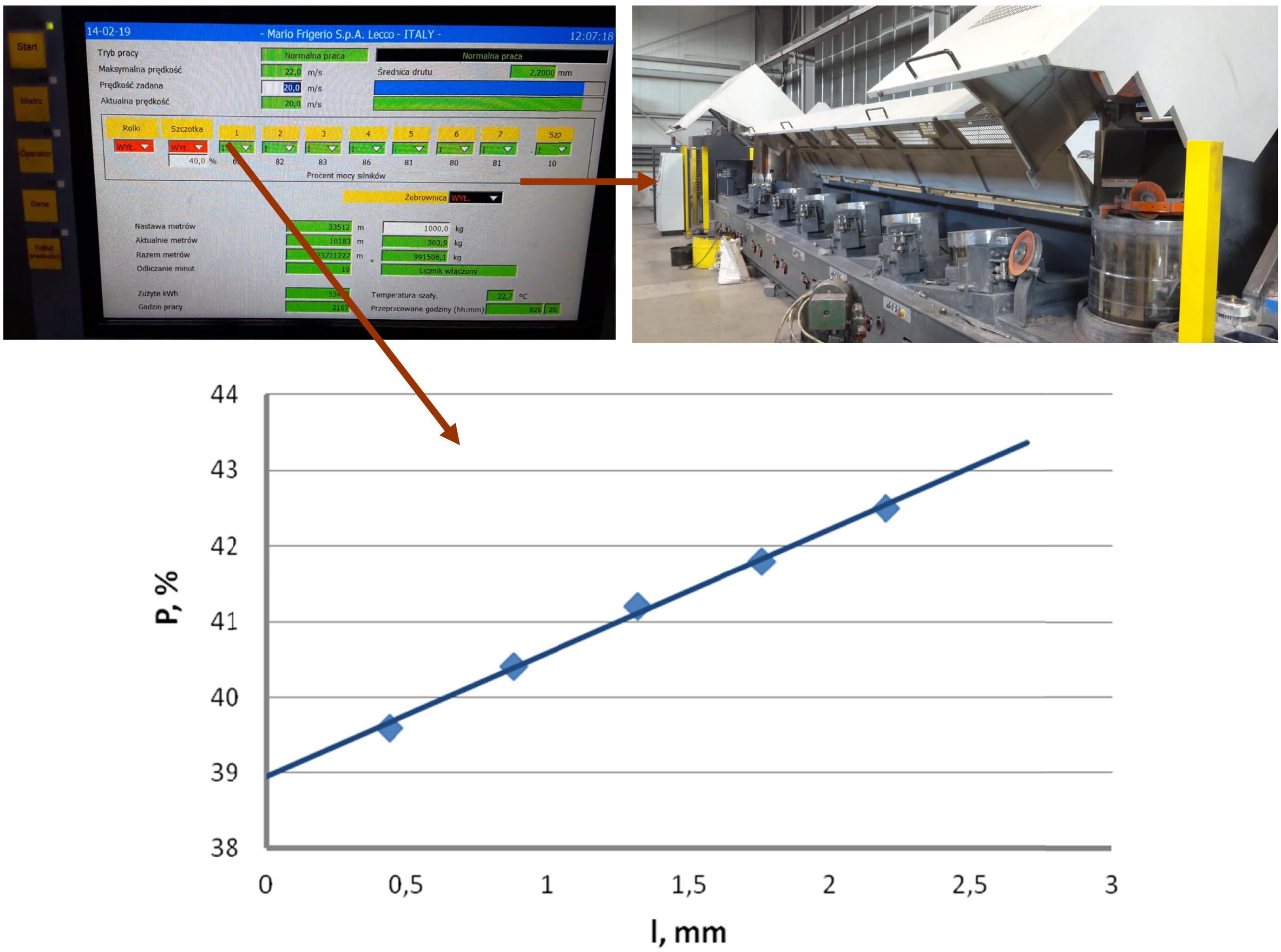

Fig. 7. Variation in percentage motor load *P* as a function of die sizing portion length *l* (drawing of wire under industrial conditions from ϕ2.46 to ϕ2.20 mm at a speed of 10 m/s)

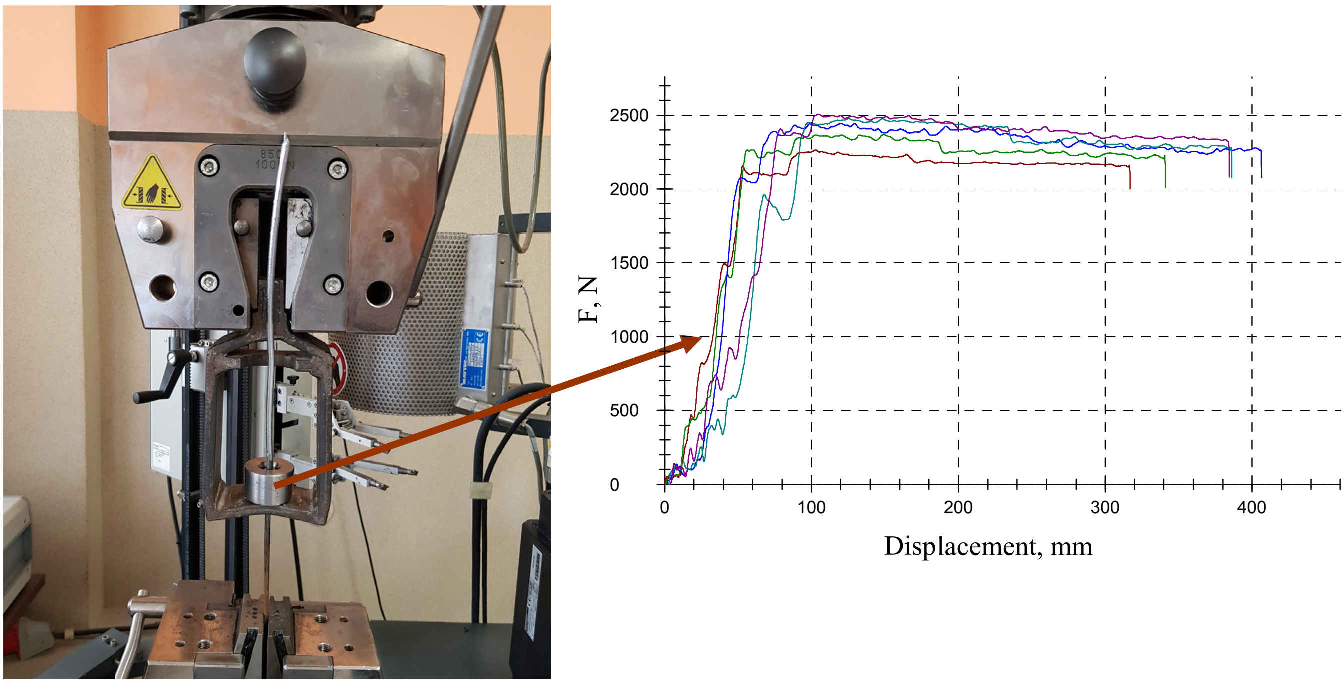

Fig. 8. Measurement of drawing force F in dies with a varying die sizing portion length l (drawing from ϕ2.46 to ϕ2.20 mm – experimentally)

differed from those obtained from industrial measurements. For a better analysis of the force parameters of the drawing process, the numerical computation results were compared with those obtained from the empirical formula and from experimental tests, Figure 10.

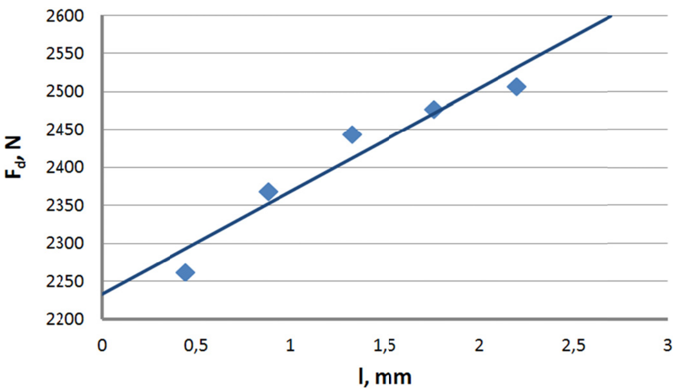

Fig. 9. Variation in drawing force F_d as a function of die sizing portion length l (drawing from ϕ2.46 to ϕ2.20 mm – experimentally)

The data in Figure 10 shows that, irrespective of the testing method, increasing the die sizing portion length causes an increase in the force parameters of the drawing process, and the differences between individual drawing variants depend on the measurement method and the conditions in which the drawing process takes place. The highest consistence in the obtained results was obtained for drawing in drawing dies with a length of $l = 0.5d$, and which was approx. 8%.

Considering the above it can be concluded that for the analysis of the effect of drawing technology on the energy and force parameters of the multi-stage steel wire drawing process

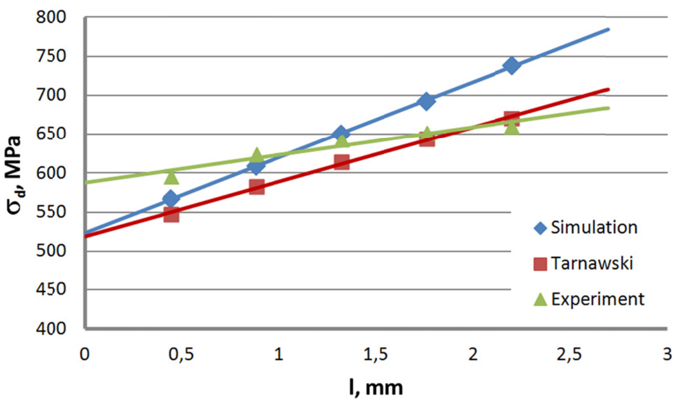

Fig. 10. Variation in drawing stress σ_d as a function of die sizing portion length l (drawing from ϕ2.46 to ϕ2.20 mm – Tarnawski's formula)

FEM-based programs, such as the Drawing 2D program, can be employed, which significantly shorten the computation time, and thus obtained results show high consistence with those obtained from actual drawing processes.

5. Conclusions

1. A relationship has been shown to exist between die sizing portion length and wire temperature and drawing stress.
2. Intensive wire heating up occurs in the die sizing portion in the multi-stage drawing process, whereas, the larger the die sizing portion length, the higher the wire surface temperature. The numerical analysis and the measurement of wire temperature under industrial conditions have demonstrated that increasing the length of the die sizing portion

from 0.2d to 1d results in an increase in wire temperature by over 30%. This phenomenon should be associated with the increase of friction forces at the wire and die interface.

3. The increase in friction forces in the die sizing portion causes an additional material effort in the drawing process. Depending on the testing method, increasing the die length l from 0.2d to 1d causes an increase in material effort by 18% on average.
4. Using the shortest possible die sizing portion length has a favourable effect on the force parameters of the drawing process, lowers the risk of wire rupture during the drawing process and reduce the energy consumption. In the authors' view, the optimal die sizing portion length is $l = 0.3d$.
5. For the analysis of the effect of drawing technology on the energy and force parameters of the multi-stage steel wire drawing process, FEM-based programs, including the Drawing 2D program, can be used, which significantly shorten the computation time, and the obtained results show high consistence with those obtained from actual drawing processes and can be used in the design of steel wire manufacturing processes.

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