High speed multi-stage drawing process of hot-dip galvanised steel wires

Maciej Suliga · Radosław Wartacz · Jacek Michalczyk

Abstract
In this paper, unique tests into the production of galvanised steel wires in industrial conditions were presented. It was demonstrated that three phenomena occur during the wire-drawing process at high speeds: namely, zinc sticking to the surface of drawing drums, zinc coating grinding caused by a larger friction surface area between the tool and the material, combined with the detachment of the zinc coating in the calibrating part of the die until the wire breaks and the drawing process is interrupted. After drawing at high speeds (over 15 m/s), the wires were characterised by a thin coat. The research carried out in the study showed a significant influence of the speed and the drawing angle on the mechanical and technological properties as well as the residual stresses in hot-dip galvanised steel wires. Depending on the speed of drawing, wires drawn in dies with an angle $\alpha = 7^\circ$, in relation to wires drawn in dies with an angle $\alpha = 3^\circ$, were characterised by 7.8–12% higher yield strength, and 3.7–7.1% higher tensile strength, 16.7% and 21.5% lower elongation, 24.3% lower reduction in area, 33% lower number of twist and bends, and 145.9% higher residual stresses.

Keywords Wire · Zinc · Hot-dip galvanising · Drawing speed · Die angle · Properties

1 Introduction
The process of manufacturing steel wire products with metallic coatings is one of the most difficult plastic forming processes, as this process consists of heat treatment, metallic coating, drawing, and final wire shaping to obtain the finished product in the form of springs, ropes, steel cord, meshes, and fasteners.

The basic metallic coatings applied to the surfaces of wires include galvanising, copper plating, brass plating, bronzing, and nickel plating [1–5]. In the case of galvanising, the most commonly used methods in the world include hot-dip galvanising, electrolytic galvanising, and thermodiffusion galvanising [6]. Hot-dip galvanising is used to galvanise wire rod and wires with a diameter greater than 1 mm. The thickness of the coat depends on the diameter of the finished product and is usually from 10 to 70 µm. This coating consists of an external, unalloyed, pure zinc layer, and an alloy layer [7]. Depending on the adopted galvanising technology, alloy additives in the form of Al, Mg, Ni, Pb, or Bi are introduced into the bath [8].

The process of drawing zinc-coated wires consists of repeatedly drawing the wire through the die and then winding it on the drum of a single or multi-stage drawing machine. Currently, in the world, in order to increase the production efficiency and reduce the costs of wire production, multi-stage drawing machines are used to draw wires even in several drafts. The wire, after passing through the die, is wound on the drum and then fed to the next die. With the next draw, the speed of drawing grows. Depending on the adopted drawing technology, drawing speeds in the last drawing stage may theoretically reach up to 40 m/s, while in the industrial practice, in the case of steel wires, such drawing speeds are not used. Increasing drawing speeds on successive drums of the drawing machine cause the occurrence of variable friction and lubrication conditions, the temperature may reach levels at which the grease disintegration of the lubricant appears, and friction increases. In consequence, the drawhole is quickly stripping [9]. The wire obtained in this process very often does not meet certain industry standards. Hence, the global drawing industry and many research
centres are looking for new solutions to improve the drawing technology. Numerous studies showed that the optimal selection of drawing machines and tools [10, 11], the geometry of the dies [12, 13], lubricants [14–16], lubricant carriers [17], the distribution of single and total reductions [18–22], and steel grade [23–25] enable a significant improvement in the quality of wires.

In contrast to bare wire drawing, when drawing wires with metallic coatings, an additional problem is the different physicochemical properties of the steel core and the soft zinc coating, which significantly hinders the correct deformation of the wire while maintaining the original surface layer of the coating. The vast majority of the available literature on multi-stage drawing of steel wires concerns bare wire drawing. However, there are few studies describing multi-stage drawing of galvanised wires [26], and the vast majority of these studies describe the drawing process on single-stage drawing machines, i.e. on machines that are not currently used for the production of wires [27].

2 Test material and drawing technologies

The material for the experiment was patented and hot-dip galvanised wire rod, made of C42D medium carbon steel, intended for the production of ropes, springs, and nets.

The wire rod with C42D carbon content after patenting and galvanising was purchased from Drumet–Manufacturer Of Wire And Steel Rope (WireCo WorldGroup Brand). The material was prepared according to a typical technology commonly used in the drawing industry. The production of galvanising of wire rod on the production line took place in several stages. In the first stage, the patenting process on the L-4 patent line began with unwinding the wire rod, rinsing in hot water. Then, the material was heated in a three-zone tunnel kiln in the temperature range from 880 to 1100 °C. After exiting the furnace, the wire rod was cooled in the fluidised bed to a temperature of about 480–520 °C. The stage of the hot-dip galvanising process was carried out using the continuous method. After the patenting process and winding on baskets, the wire rod was placed on decoilers, where it was unrolled and subjected to the process of etching in hydrochloric acid, fluxing, and drying. Then, immediately after drying, the heated wire was passed through a zinc bath with a temperature of 440–460 °C.

Figure 1 presents the microstructure, where the typical zinc coating is made of the unalloyed phase and zinc-iron phases.

After hot-dip galvanising, the wire rod was delivered to the company “STALEX” s.c., where the drawing process took place in industrial conditions. The drawing process was carried out on the multistage Mario Frigerio model S560 / 7, currently widely used in the world, adapted to drawing e.g. galvanised steel wire rod. The process of drawing wire rod with a diameter of 5.5 mm to a wire with a diameter of 2.2 mm was carried out in 7 drafts with the use of conventional dies with a drawing angle $\alpha = 3, 4, 5, 6, 7^\circ$ (Table 1). As a lubricant, the multi-component drawing powders

---

**Fig. 1** The wire rod layer microstructure after the hot-dip galvanising, longitudinal section
consisting of inorganic additives and a mixture of calcium and sodium soaps were used.

### Table 1 Wire drawing diagram, where $G_p$ is single reductions, $G_c$ is total reductions, and $v$ is the drawing speed

| Draw no. | 0 | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|---------|---|-----|-----|-----|-----|-----|-----|-----|
| $\phi$, 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 |

#### Drawing speeds in individual draws

| $v$, m/s | 1.06 | 1.43 | 1.90 | 2.47 | 3.15 | 4.00 | 5   |
|----------|------|------|------|------|------|------|-----|
|          | 2.12 | 2.86 | 3.80 | 4.94 | 6.31 | 8.00 | 10  |
|          | 3.17 | 4.28 | 5.70 | 7.41 | 9.46 | 12.00 | 15 |
|          | 4.22 | 5.70 | 7.59 | 9.88 | 12.62 | 16.00 | 20 |

### 3 Wire surface layer analysis

In the process of drawing galvanised wires, lubrication conditions affect the structure and properties of the wire surface layer. Figure 2 shows the significant effect of the angle and speed of drawing on the lubrication conditions. As the speed of drawing increases, the amount of lubricant decreases. Wires drawn at a speed of 20 m/s, compared to wires drawn at a speed of 5 m/s, depending on the drawing angle, were characterised by 58.9 to 88.4% less grease.

The negative influence of the drawing speed on the lubrication can be partially eliminated by the use of smaller angles of the working part of the die. The lubrication improvement for wires drawn with small angles should be seen, among others, at lower wire pressures in the die. This creates more favourable conditions for the applying grease in the drawing process. In order to estimate the influence of the drawing angle and speed on the change in the weight of the zinc coating, the study determined the amount of zinc on the surface of $\phi 2.2$ mm wires drawn in die with a drawing angle $\alpha = 3, 4, 5, 6, 7^\circ$, at drawing speed 5, 10, 15, and 20 m/s (Fig. 3).

The results presented in Fig. 3 confirmed that the angle and speed of drawing affected the weight change of the zinc coating on the wires. The analysis of the change in the amount of zinc as a function of the drawing angle showed that, at low drawing speeds, of the order of 5 m/s, the differences in the thickness of the zinc coating do not exceed 6%, while greater differences are visible only at drawing speeds above 10 m/s. For speed 20 m/s, differences in thickness of zinc coating reach up to 25%.

**Fig. 2** The amount of lubricant depending on the angle and speed of drawing

![Lubricant graph](image-url)
Apart from specific mechanical properties, the wires require a minimum zinc thickness. The PN-EN 10,244–2 standard, commonly used in the industry, determines the minimum mass of the coating that should be on the wire by qualifying them to the appropriate classes. The galvanised 2.2 mm wires after plastic processing are usually placed in class B (δ ≥ 125 g/m²). The data in Fig. 4 showed that, at the speed of 5 m/s, the remaining weight of the zinc coating is so large and the differences between the analysed variants are small that, regardless of the drawing angle, all analysed variants were categorised in the higher AB class (δ ≥ 170 g/m²). The speed of 10 m/s contributed to the creation of larger differences in the thickness of the zinc coating and revealed the negative effect of high die angles on the zinc thickness. The wires drawn with an angle α = 7° were categorised in the lower B class, while the remaining variants were classified as AB. A further growth to the speed of 15 m/s caused a significant drop in the weight of zinc. In this case, only wires drawn in dies with an angle α = 3° retained the AB class, while the other variants were classified as B. The greatest decrease in the coating thickness was recorded at the speed of 20 m/s, and the low drawing angle only partially inhibited the decrease in the amount of zinc on the wires. With such a high drawing speed, regardless of the size of the angle α, neither variant had an AB class coating. Drawn wires in dies with an angle α = 3, 4, 5° (v = of 20 m/s) were categorised into class B, while the remaining variants fell into class C. The differences in the weight of the zinc coating between the variants amounted to 25%.

Thus, the amount of zinc on the final wire depends on the angle of the working part of die and the drawing speed. Industrial galvanised wire drawing tests have shown that the conventional method of drawing galvanised wire at a high speed (v = 20 m/s) is unstable. The hypothesis of intense heating of the zinc coating is confirmed by observations carried out during industrial wire drawing tests, which show that drawing at such speed causes zinc to detach from the wire surface, and a soft zinc coating to stick to the drawing machine drums (Fig. 4).

During high speed drawing process, regardless of the adopted drawing angle, the wire was broken. Industrial drawing tests have shown an interesting relationship between the drawing angle, the size of the zinc coating, and the process stability. Wires drawn with an angle α = 3° had a thicker zinc coating, but the wire breakage was fastest in the multi-stage drawing machine. For angle α = 7°, an inverse dependence was noted. In this variant, the lowest thickness of the zinc coating was observed, but the drawing process took much longer before the wire broke in the drawing machine.

In summary, it can be stated that the thickness of the zinc coating on the wire and the stability of the drawing process at the speed of 20 m/s depend on the angle of the working part of the die. A smaller drawing angle means a smoother contact between the wire and the die, but, at the same time, a longer contact surface of the tool increases friction and temperature. This leads to the plasticisation of the zinc coating and an increase in its tendency to stick to the die. Hence, there are two phenomena in the drawing process: namely, grinding the zinc coating caused by a larger friction surface
between the tool and the material, combined with breaking of the zinc coating in the calibrating part of the die, leads to breaking of the wire and interruption of the plastic working process. The remains of the ground and partially torn coating, along with the burnt grease covering it, are “thrown” by the die, as shown in Fig. 5.

Unlike the wire drawing process in dies with small angles $\alpha$, when drawing with an angle of 7°, the weight loss of the zinc coating is caused not only by grinding but also by shearing of the zinc coating. At large die angles, high shear stresses occur at the wire entry to the die, which significantly increase the tendency to break the zinc coating (Fig. 6).

Long stretches of the stripped zinc coating accumulate in the die entry cone during the drawing process. Over time, a wedge forms from the stripped-off zinc coating, preventing lubrication. Under the influence of the “zinc wedge”, high drawing resistances are also created, which makes the drawing process on the multi-stage drawing machine unstable, and the wire breaks.

To sum up, the factors determining the stability of the drawing process of galvanised steel wire at high speeds (over 15 m/s)
include friction, temperature, and shear stresses. According to the authors, the main factors causing wire breakage when drawing with small angles $\alpha$ are phenomena of friction and softening of the zinc coating, while at large angles $\alpha$, those include shearing of the zinc coating in the die approach angle die. This, in turn, is expected to influence the conditions of deformation of the zinc coating on the wire surface roughness.

The examination of the surface topography of zinc-coated wires after the drawing process was carried out on a Form Talysurf 50e profilometer. Figure 7 shows an example of a profilogram of the wire surface.

To illustrate the variations in wire surface texture, the profile height – $R_t$ and $R_z$ – and deviation parameters – $R_a$ and $R_q$ – were used for analysis.

$R_t$ is the total value of the profile depth $R_v$ and profile height $R_p$ within the measuring length under examination, as per Formula (1):

$$R_t = R_p + |R_v|$$  \hspace{1cm} (1)

$R_z$ is the arithmetic mean of the absolute values of the heights of the five largest elevations and the five largest depressions of the roughness profile, as calculated from Formula (2):

$$R_z = \frac{\sum_{i=1}^{5} |y_{pi}| + \sum_{i=1}^{5} |y_{ri}|}{5}$$  \hspace{1cm} (2)

$R_a$ is the mean of profile deviations from the average line defined by Formula (3):

$$R_a = \frac{1}{L} \int_0^L |y(x)|dx$$  \hspace{1cm} (3)

where $L$ is the length of the examined segment and $y(x)$ is the roughness profile equation.

$R_q$ is the quadratic mean of the values of profile deviations from the average line within the examined measuring length, defined by Formula (4):
Figures 8, 9, 10 and 11 represent the effect of drawing speed and drawing angle on the profile height and profile deviation parameters.

The analysis of the surface roughness of zinc-coated wires has demonstrated that drawing technology significantly influences the orientation of the geometric elements of the surface. The data represented in Figs. 8, 9, 10 and 11 show that with the increase in drawing speed, the profile height parameters and profile deviation parameters of zinc-coated wires increase. Wires drawn at a drawing speed of 20 m/s had roughness parameters, on average, by approx. 30% higher, compared to those drawn at a drawing speed of 5 m/s. The increase in the surface roughness of wires drawn at high speeds can be sought, inter alia, in the deterioration in lubrication conditions and the intensive heating up of the top layer of the wire. At drawing speeds of 5–10 m/s, a wire surface forming

\[ R_q = \sqrt{\frac{1}{L} \int_0^L y^2(x) \, dx} \]  

Fig. 7 Surface texture of \( \phi 2.2 \) mm-diameter wire for the \( \alpha = 3^\circ \) variant

Fig. 8 The profile height parameter \( R_t \) depending on the angle and speed of drawing

\[ \text{Fig. 7 Surface texture of } \phi 2.2 \text{ mm-diameter wire for the } \alpha = 3^\circ \text{ variant} \]

\[ R_q = \sqrt{\frac{1}{L} \int_0^L y^2(x) \, dx} \]  

\[ \text{Fig. 8 The profile height parameter } R_t \text{ depending on the angle and speed of drawing} \]
factor is the lubricant. The insufficient quantity of the lubricant failed to separate the friction surfaces of the wire and the die. A much harder and smoother die surface caused surface rises on the zinc coating to wear off and deform. By contrast, at higher drawing speeds, high temperature causes a thermoplastic layer to form at the material and tool interface, leading to damage to the top wire layer and an increase in its roughness. In extreme cases, when drawing at a speed of 20 m/s, seizures occur on the wire surface (Fig. 12).
Surface roughness examinations have shown that, in the zinc-coated steel wire multi-stage drawing process, the drawing angle significantly influences the profile height and profile deviation parameters, with differences between the analysed variants being larger, the higher drawing speed is. Wires drawn at the drawing speed 20 m/s in dies with the angle $\alpha = 7^\circ$ show, on average, profile height parameters smaller by 15% and profile deviation parameters smaller by 34%, compared to wires drawn in dies with the angle $\alpha = 3^\circ$. In the author's view, the differences in surface roughness between wires drawn at different working portion angles can be sought in the different wire and die contact length. The difference in wire and die contact length between the angles 3 and $7^\circ$, is, on average, about 70%, depending on the single reduction. Increasing the wire and die contact length in multi-stage drawing causes an increase in friction surface at the wire-die interface, which leads to additional heating up of the top layer zinc coating, resulting in its additional "softening" and "sticking" onto the die. As a consequence, zinc-coated wires drawn at smaller angles are characterised

---

**Fig. 11** The profile deviation parameter $R_q$ depending on the angle and speed of drawing

**Fig. 12** Reeled wire coils with visible zinc coating surface seizures occurred in drawing at a speed of 20 m/s
by a more varying surface topography with larger profile hollows and rises.

4 Mechanical properties

The analysis of the influence of the drawing technology on the properties of the zinc coating and the steel core is very difficult and complex. The angle and speed of drawing affect the deformation and cracking of the zinc coating as it is drawn through the die. This results in the detachment of pieces of the metallic coating with grease applied to its surfaces. As a consequence, the wire entering the next die is partially covered with grease, in the areas where the zinc has crumbled, we have a “ragged” surface characterised by very high roughness, and the amount of grease remaining on the wire surface is small. In addition, the remnants of zinc are drawn into the drawing die by the wire, clogging them, which increases the deformation resistance, friction, and breaks of the wire. The deterioration of the friction conditions at the contact of the wire and the drawing die also affects the flow of the steel core. In the drawing process, the total wire deformation is the sum of homogeneous deformations resulting from the reduction of the cross-section and form deformations (unnecessary deformations) resulting from the macro-cutting of the wire surface layers. The shear deformations depend on the friction conditions and the geometry of the dies, the lowest values being obtained at optimal drawing angles \( \alpha \). Contrary to drawing bare (bare) wires, when drawing wire with a metallic coating, the metallic coating also has an additional influence on the strengthening of the steel core. With the right choice of die geometry, dies, and drawing speed, this coating can act as an undercoat layer (e.g. copper coatings), which results in more effective lubricant overlap, reduction of friction, and wire strengthening. The study showed that when drawing wire with a soft zinc coating, in extreme cases, it may break and the drawing conditions may deteriorate. Hence, it seems important to analyse the influence of friction conditions on the wire contact, the top layer of the wire (zinc coating), and the strengthening of the steel core, which determines the strength, plastic, and technological properties of the wire.

Tests for the mechanical properties of the wire on a Zwick/Z100 testing machine and on a wire twisting and bending test device were done. During the torsion test, specimens with dimensions of \( 100 \times d \) (where \( d \) is wire diameter) were loaded with an axial force being equal to 2% of the maximum breaking force. To determine the number of bends, the specimens were bent on rollers of a size of \( \phi 20 \) mm. Research on the mechanical properties of 2.2 mm wires drawn according to individual technological variants is presented in Figs. 13, 14, 15, 16, 17, 18 and 19.

The strength properties presented in Figs. 13 and 14 showed that the drawing technology significantly affects the strength properties of galvanised steel wires. Depending on the speed of drawing, wires drawn in dies with an angle \( \alpha = 7^\circ \), in relation to wires drawn in dies with an angle \( \alpha = 3^\circ \), were characterised by 7.8–12% higher yield
strength, and 3.7–7.1% higher tensile strength. The higher the drawing speed, the greater the differences between the analysed variants. Form deformations resulting from macro-shearing of the wire surface layers are a factor that has a significant effect on the strength properties of the wires. This leads to the formation of a heterogeneous distribution of plastic strains on the cross-section and an intensive strengthening of the surface layer of the wire. Using too-high angles in the drawing process of galvanised wires $\alpha$ contributes to the increase in strength properties, confirmed by higher values YS and UTS and the simultaneous deterioration of their plastic properties, which is confirmed by the results presented in Figs. 15, 16 and 17.

Fig. 14 Tensile strength UTS depending on the angle and speed of drawing

![Graph](image1)

Fig. 15 Uniform elongation UEL depending on the angle and speed of drawing

![Graph](image2)
Figures 15, 16 and 17 show regardless of the drawing speed, the angle $\alpha$ affects the plastic properties to a much greater extent than the strength properties of the wire. The differences between the analysed variants increased and exceeded 20%. Wires drawn in dies with an angle $\alpha = 7^\circ$, in relation to wires drawn in dies with an angle $\alpha = 3^\circ$, at the drawing speed of 20 m/s, were characterised by 16.7% and 21.5% lower elongation, and 24.3% lower reduction in area.
The conducted tests also confirm the negative impact of the drawing speed on the wire plasticity. The increase in speed caused a decrease in the plastic properties of the wire, which should be associated with the deterioration of the lubrication conditions and, consequently, an increase in friction on the contact surface of the wire/die (Fig. 2). Thus, the use of high-speed galvanised steel wires and conventional dies with high values of the $\alpha$ angle in the production...
process leads not only to significant reduction of the thickness of.
coat, but also to a deterioration of its susceptibility to plastic
deformation. These wires are a semi-finished product for
further cold plastic processing. When forming a wire into a
rope or a spring, the wire breaks very frequently. This thesis
is confirmed by technological tests of the wire, in which the
number of twists and bends of the wire is determined. The
conducted tests clearly show that both the speed and α angle
substantially affect the technological properties of the wire
(Figs. 18 and 19).

In summary, it can be concluded that, when drawing gal-
vanised wires, an increase in the drawing angle causes a
decrease in the number of twists and bends, and the use of
high drawing speeds, of the order of 20 m/s, results in a sig-
nificant decrease in the number of twists. Differences in the
obtained number of twists between drawn wires exceeded
33%. Such a large drop in the number of twists significantly
limits the use of wires as a material for springs or ropes.

5 Residual stresses in steel wires

Residual stresses significantly affect the quality of galva-
nised steel wire, as they may be the source of wire crack-
ing during its forming into a spring, rope, etc. In addition,
in the case of wires with an anti-corrosion coating, these
stresses can also reduce their corrosion resistance. As in
the case of mechanical properties, the technology of drawing
wires with a metallic coating influences the residual stresses
in the wires after the drawing process. The development of
residual stresses is described by mechanical, thermal,
and phase transformation models. The mechanical model
that has the greatest impact on the formation of residual
stresses in wires after the drawing process is based on the
distribution of longitudinal stresses. The worse the friction
conditions and the greater the deformation resistance, the
more heterogeneous the distribution of longitudinal stresses
and the greater the residual stress. Hence, according to the
authors, the change in the angle and speed of drawing steel
wires covered with a thin and soft zinc coating affects the
value of residual stresses. In connection with the above, the
paper determines the effect of the galvanised wire drawing
technology on the first type longitudinal residual stresses.
To determine the residual stresses, the method of longitu-
dinal wire cutting was used [28, 29], as shown in Fig. 20.
From the equation of the moments of forces acting on the
cut wire, the following expression is obtained for the circu-
lar-symmetric distribution to determine the stresses on the
outer surface of the wire (5) presented in [29]:

$$\sigma_w = 1.3176 \cdot E \cdot R \cdot \frac{h}{l^2}$$

where:
- $\sigma_w$ – longitudinal residual stress on the wire surface, MPa;
- $E$ – Young’s module, MPa;
- $R$ – wire diameter, mm;
- $h$ – parting of the wire ends, mm;
- $l$ – cutting length, mm.

The test results are presented in Figs. 21 and 22.

The residual stress tests in steel wires showed that, as in
the case of mechanical properties, the friction conditions at
the wire/die interface, depending on the drawing technology

![Diagram of wire cutting on a spark wire cutting machine](image)
and the condition of the zinc coating, affect the properties of the wires. Contrary to drawing of bare wires, an additional component influencing the residual stresses is the zinc coating. Research presented, i.e. in Figs. 4, 5 and 6, showed the possibility of the coating softening, cracking, and detachment of zinc pieces from the wire surface, which in the drawing process causes additional deformation resistance, increased friction, and residual stresses. The test results for the measurement of residual stresses included in Figs. 21 and 22 showed that, along with the increase of the drawing die and speed, the type I longitudinal residual stresses in galvanised steel wires increase. Drawn wires in dies 7° in relation to the 3 variant, depending on the drawing speed, have from 95.1 to over 145.9% higher residual stresses.

Fig. 21 The effect of the drawing angle \( \alpha \) on longitudinal residual stresses in wires with a diameter of 2.2 mm

Fig. 22 The effect of the drawing speed \( v \) on the longitudinal residual stresses in the wires with a diameter of 2.2 mm
Higher values of residual stresses in wires drawn with large angles, especially with angle $\alpha = 7^\circ$, should be associated with greater strengthening for this variant due to the occurrence of larger deformations in the surface layer of the wire. Regarding the drawing speed, it can be stated that the source of higher residual stresses in high-speed drawn wires, regardless of the $\alpha$ angle, was primarily poor lubrication conditions causing an increase in deformation heterogeneity, as well as intense heating of the wire surface layer. An increase in the temperature of wires during drawing at speeds of 15–20 m/s could cause the occurrence of thermal stresses in the wire, which could be the source of additional residual stresses.

6 Conclusions

The thickness of the zinc coating on wires depends mainly on the drawing speed. An increase in the drawing speed causes the drawing conditions to deteriorate, which leads to a decrease in the amount of zinc on the surface of the wires.

Industrial tests of galvanised wire drawing with 20 m/s speed showed that the drawing process of a galvanised is unstable, and the smaller the drawing angle, the more frequent the wire breaks.

Factors determining the stability of the drawing process of galvanised steel wire at high speeds (over 15 m/s) include friction, temperature, and shear stresses. The main factors causing wire breakage when drawing in dies with small angles $\alpha$ are phenomena of friction and softening of the zinc coating, while at large angles $\alpha$, those include shearing of the zinc coating in the die approach angle.

An increase in the drawing speed and angle causes an increase in strength properties and a decrease in plastic and technological properties of the wire.

The technology of galvanised steel wire drawing significantly affects the level of residual stress in the wires after the drawing process. With an increase in the angle and the drawing speed, the first type longitudinal residual stress increases.

The selection of the multi-stage drawing technology of galvanised steel wires is a complex issue. The conducted tests showed that the optimal value of the drawing angle is the angle $\alpha = 5^\circ$, and the drawing speed should not exceed 15 m/s. These parameters make it possible to obtain wires with good mechanical and technological properties and a relatively thick zinc coating.

The obtained test results can be used in the design of multi-stage drawing technology of galvanised steel wires.

Author contribution The three authors have made relevant contributions to the experiment, data processing, or thesis writing.

Available data and material The data and materials of this article are obtained in the experiment and are real data.

Declarations

Ethics approval This article has no problems with ethics approval and it has been approved by all parties.

Consent to participate All parties have agreed.

Consent for publication Agree to publish this manuscript.

Conflict of interest The authors declare no competing interests.

References

1. Roger N (2011) Wright: Wire technology. Elsevier, Process engineering and metallurgy
2. Golis B, Pilarczyk JW, Dyja H, Błażejowski Z, Shemenski RM (1999) Steel tire cord technology. Wire Assoc Int
3. Pinto G, Silva FIG, Baptista A, Fecheira JS, Campilho RDSG, Viana F (2020) Studying the ZnO formation in coated steel wire ropes for the automotive industry. Procedia Manuf 51:912–919. https://doi.org/10.1016/j.promfg.2020.10.128
4. Tintelecan M, Iluju-Varvara DA, Alabanda OR, Sas-Boca IM (2020) A technical version of achieving a brass coated surface on steel wires. Procedia Manuf 46:12–18. https://doi.org/10.1016/j.promfg.2020.03.003
5. Wartacz R (2019) Analiza teoretyczno-doświadczalna ciągnienia wielostopniowego drutów oczynkowanych ze stali C42D, praca doktorska (Theoretical and experimental analysis of the multistage drawing of galvanized wires from C42D steel, doctoral thesis). Częstochowa University of Technology, Częstochowa
6. Kania H, Sipa J (2019) Microstructure characterization and corrosion resistance of zinc coating obtained on high-strength grade 10.9 bolts using a new thermal diffusion process. Materials 12(9):1400. https://doi.org/10.3390/ma12091400
7. Kania H, Mendala I, Kozuba I, Saternus M (2020) Development of bath chemical composition for batch hot-dip galvanizing - a review. Materials 13(18):4168. https://doi.org/10.3390/ma13184168
8. Kania H, Saternus M, Kudláček J (2020) Structural aspects of decreasing the corrosion resistance of zinc coating obtained in baths with Al, Ni, and Pb additives. Materials 13(2):385. https://doi.org/10.3390/ma13020385
9. Suliga M (2014) Analysis of the heating of steel wires during high speed multipass drawing process. Arch Metall Mater 59(4):1475–1480. https://doi.org/10.2478/amm-2014-0251
10. El Amine K, Larsson J, Pejryd L (2018) Experimental comparison of roller die and conventional wire drawing. J Mater Process Technol 257:7–14. https://doi.org/10.1016/j.jmatprotec.2018.02.012
11. Bitkov V (2006) Research of wire drawing under conditions of hydrodynamic friction. Wire Cablo Technol Int 94–97
12. Toribio J, Lorenzo M, Vergara D, Kharin V (2014) Influence of the die geometry on the hydrogen embrittlement susceptibility of cold drawn wires. Eng Fail Anal 36:215–225. https://doi.org/10.1016/j.engfailanal.2013.10.010
13. Tintelecan M (2017) Ioana Monica Sas-Boca, Dana-Adriana Iluju-Varvara: The influence of the dies geometry on the drawing force for steel wires. Procedia Eng 181:193–199. https://doi.org/10.1016/j.proeng.2017.02.369
14. Sas-Boca IM, Tintelecan M, Pop M, Iluju-Varvara DA, Mihu AM (2017) The wire drawing process simulation and the optimization
of geometry dies. Procedia Eng 181:187–192. https://doi.org/10.1016/j.proeng.2017.02.368
15. Xu C, Peng Y, Zhu Z, Tang W, Huang K (2021) Influence of different mineral particles in lubricating grease on the fretting behavior between steel wires under different contact forms. Wear 472–473. https://doi.org/10.1016/j.wear.2021.203700
16. Roger N (1997) Wright: Physical conditions in the lubricant layer. Wire J Int 88–92
17. Damm H (2011) Dry drawing lubricants and borax. Wire J Int 68–70
18. Lee SK, Ko DC, Kim BM (2009) Pass schedule of wire drawing process to prevent delamination for high strength steel cord wire. Mater Des 30(8):2919–2927. https://doi.org/10.1016/j.matdes.2009.01.007
19. Kim J-H, Ko D-C, Kim B-M (2019) New tandem drawing process through non-driven four roll-die and converging die. J Mater Process Technol 263:470–478. https://doi.org/10.1016/j.jmatprotec.2018.08.016
20. Lee S-K, Lee S-B, Kim B-M (2010) Process design of multi-stage wet wire drawing for improving the drawing speed for 0.72wt% C steel wire. J Mater Process Technol 210(5):776–783. https://doi.org/10.1016/j.jmatprotec.2010.01.007
21. Celano G, Fichera S, Fratini L, Micari F (2001) The application of AI techniques in the optimal design of multi-pass cold drawing processes. J Mater Process Technol 113(1–3):680–685. https://doi.org/10.1016/S0924-0136(01)00686-0
22. Kustra P, Milenin A, Byrskा-Wójcik D, Grydin O, Schaper M (2017) The process of ultra-fine wire drawing for magnesium alloy with the guaranteed restoration of ductility between passes. J Mater Process Technol 247:234–242. https://doi.org/10.1016/j.jmatprotec.2017.04.022
23. Zelin M (2002) Microstructure evolution in pearlitic steels during wire drawing. Acta Mater 50:4431–4447
24. Bhattacharya B, Bhattacharyya T, Haldar A (2020) Influence of microstructure on the mechanical properties of a pearlitic steel. Metall Mater Trans A 51A:3614–3626. https://doi.org/10.1007/s11661-020-05793-2
25. Langford G (1977) Deformation of pearlite. Metall Trans A 8:861–875. https://doi.org/10.1007/BF02661567
26. Suliga M, Wartacz R, Hawryluk M (2020) The multi-stage drawing process of zinc-coated medium-carbon steel wires in conventional and hydrodynamic dies. Materials 13:4871. https://doi.org/10.3390/ma13214871
27. Golis B (1984) Methods of assessing selected properties of galvanized and non-galvanized linear wires (in Polish). Metal products, Research and Development Center of the Metal Products Industry in Krakow 2:1–30
28. Schepers A, Peiter A (1959) Untersuchung der technologischen Eigenschaften und Eigenspannungen gezogener Automatensstähle. Stahl Eisen 79:337–349
29. Knap F, Karuzel R, Cieslak L (2004) Drawing of wires, rods and pipes (in Polish), Metallurgy No. 36, Publisher of the Faculty of Process, Materials and Applied Physics, Częstochowa University of Technology, Częstochowa

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.