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THE INFLUENCE OF THE ANGLE OF WORKING PART OF DIE ON THE ZINC COATING THICKNESS AND MECHANICAL PROPERTIES OF MEDIUM CARBON STEEL WIRES

The paper discusses experimental studies to determine the effect of the die working portion angle on the lubrication conditions, zinc coating thickness and the mechanical properties of medium-carbon steel wires. The test material was 5.5 mm-diameter wire rod which was drawn into 2.2 mm-diameter wire in seven draws at a drawing speed of v = 10 m/s. Conventional drawing dies of a working portion angle of α = 3, 4, 5, 6, 7°, respectively, were used for the drawing process. After the drawing process, the quantity of the lubricant on the wire surface and the thickness of the zinc coating were determined in individual draws. Testing the finished 2.2 mm-diameter wires for mechanical properties, on the other hand, determined the effect of the die working portion on the yield point, tensile strength, uniform and total elongation, reduction in area, the number of twists and the number of bends.

Keywords: wire, die angle, hot dip galvanizing, mechanical properties

1. Introduction

Steel wires and wire products have wide application in industry. Hence, besides uncoated wires, also zinc, tin, copper, nickel, bronze and brass-coated wires make up a considerable part of production [1].

The most widespread method of protecting wire against corrosion is currently hot-dip metal coating commonly known as hot galvanizing [2,3]. A factor decisive to a zinc coating is the chemical composition of the galvanizing bath. Presently, these baths always contain alloy additions, such as Al, Ni, Pb [4] and Bi [5]. The formation of a zinc coating is very complex and proceeds as a result of the simultaneously occurring partial processes of reaction diffusion, dissolution and secondary crystallization. To improve the corrosion resistance of coatings, Al and Mg are added to the bath [6]. The rate of zinc coating formation and the microstructure of the coating depend not only on the galvanizing technology alone, but also on the chemical composition of the steel, and particularly the Si content [7].

Regardless of the coating type, coated wires are required to have appropriately thick, homogeneous and continuous coat, while retaining specified mechanical properties that meet applicable industry standards. This compels the manufacturers to continuously improve their manufacturing technology.

Therefore, factors such as drawing speed, drawing die type, lubrication conditions and the values of single and total cross-section reduction are all important in the wire production process [8-10]. Study [1] has shown that, in multi-stage drawing, a reduction of zinc coat mass occurs on the wire surface, with the zinc losses increasing as the drawing speed increases. Literature [1,11-14] show that the appropriate selection of the die working portion enables a significant improvement in drawing conditions and steel wire properties. However, the literature does not describe the effect of die geometry on the galvanized steel wire multi-stage drawing process and the properties of the drawn wire.

2. Material and drawing technology

For the drawing process, 5.5 mm-diameter wire rod was used, which had undergone a hot dip galvanizing process, Figure 1. After galvanizing, the wire rod was drawn into a 2.2 mm-diameter wire in 7 draws at a drawing speed of 10 m/s, Table 1. In drawing process the conventional dies of a die approach angle α = 3, 4, 5, 6, 7 were used.

TABLE 1

The distribution of single reductions, G_p; total reduction, G_c; and drawing speed, v

Draw no.	**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

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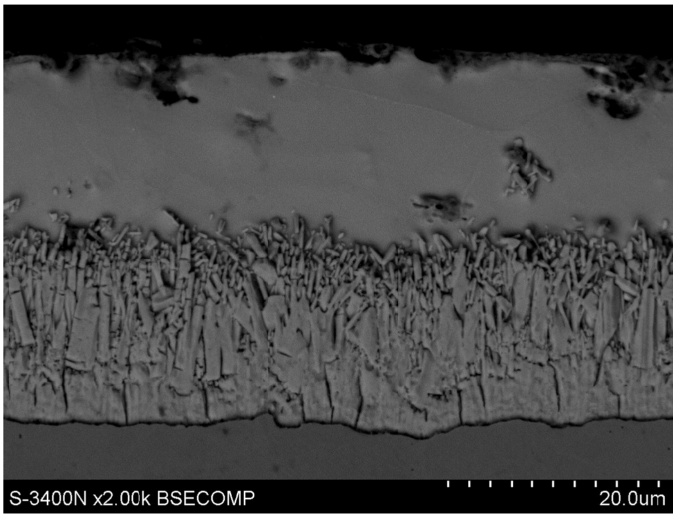

Fig. 1. Coat cross-section (SEM) microstructure for galvanized C42D steel wire rod

3. Lubrication conditions

To determine the effect of drawing angle on the lubrication conditions, ten 100 mm-long specimens were taken for each drawing variant. After weighing the specimens on a laboratory balance, it was proceeded with the removal of the lubricant layer using sodium hydroxide (NaOH) and technical acetone. After the specimens had completely dried up, they were weighed again. From the mass difference, the quantity of lubricant on the wire surface was determined. The tests to determine the effect of drawing angle on the lubrication conditions were carried out for wires of a diameter from 4.73 do 2.2 mm. The test results are represented in Figure 2-3.

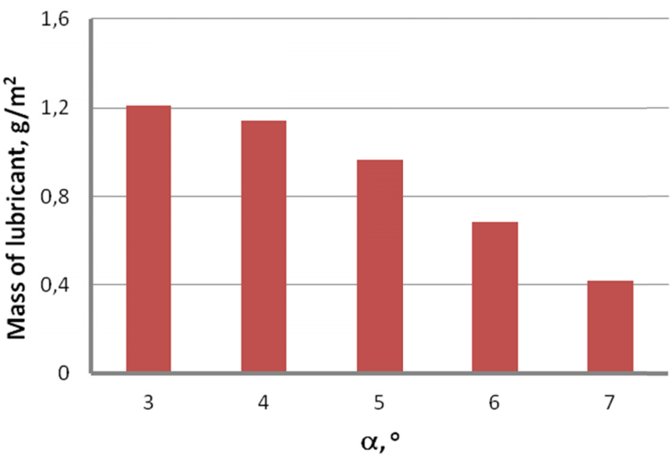

Fig. 2. The effect of drawing angle α on the mass of lubricant on the surface of 2.2 mm-diameter wires

The test results illustrated in Figure 2-3 confirm the significant effect of drawing angle on the lubrication conditions. Using smaller angles of the die working portion improves lubrication conditions. It follows from Figure 3 that as the total reduction increases, the differences in the quantity of lubricant on the surface of wires drawn with the angle $\alpha = 3$ and $\alpha = 7°$, respectively, grow, and amount to over 65% at a total reduction of $G_c = 84\%$. The improvement of lubrication conditions for wires drawn at small angles is to be sought in smaller wire loads in the die, among other factors. This creates more advantageous conditions for lubricant spreading in the drawing process.

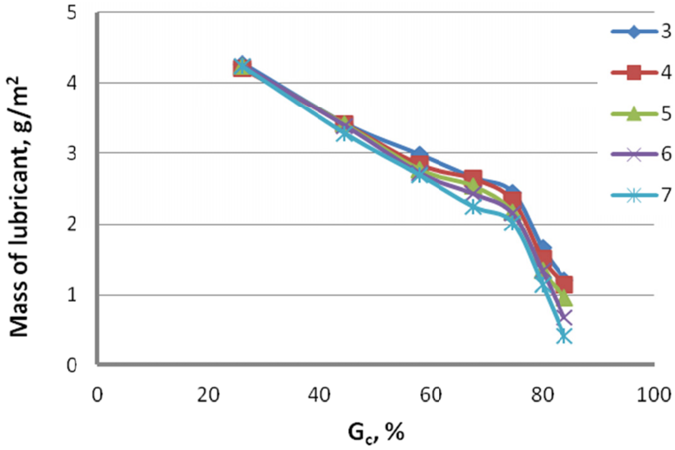

Fig. 3. Variation in lubricant mass on the wire surface at an angle of $\alpha = 3\text{-}7°$ as a function of the total reduction

4. Zinc coat thickness tests

To determine the effect of drawing technology on the thickness of the zinc coat, the coat thickness in individual draws was determined for wires drawn in the conventional dies with a drawing angle of $\alpha = 3, 4, 5, 6, 7°$, respectively. Samples of wire free from surface damage or burrs were selected for testing. Test variants consisted of 10 straight galvanized wires, each of a length of 100 mm, which were cleaned, degreased and then weighed. Next, the coat deposited on the wire was removed as per standard PN-EN 10244-1. The test results are illustrated in Figures 4-5.

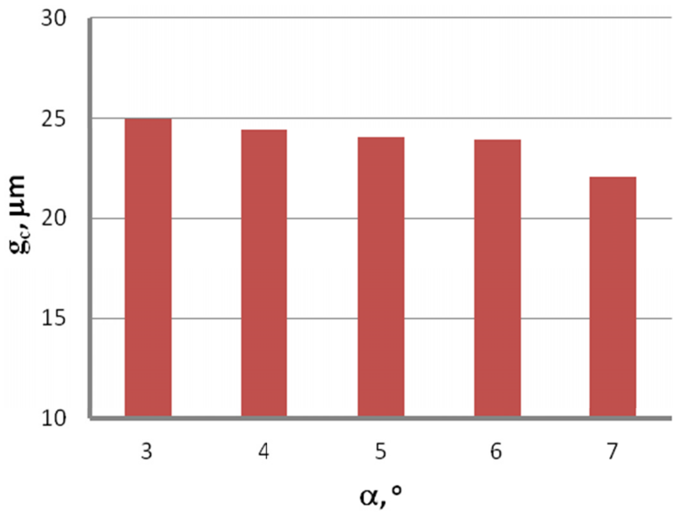

Fig. 4. The effect of drawing angle α on the zinc coat thickness, g, for 2.2 mm-diameter wires

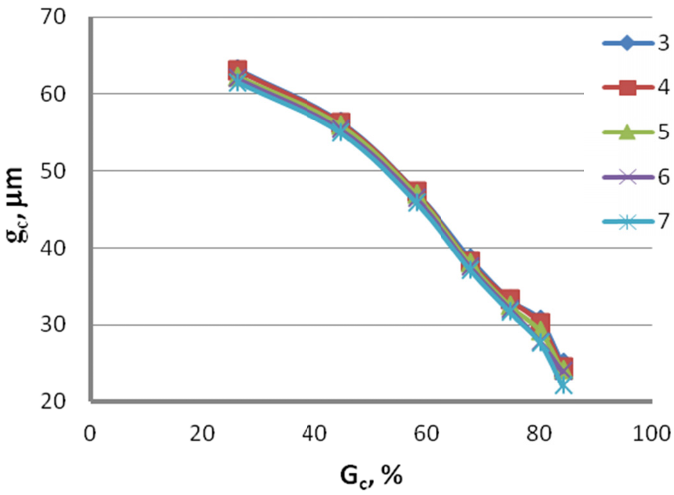

Fig. 5. Variation in zinc coat thickness *g* as a function of the total reduction

From the data in Figures 4-5 it can be found that the drawing angle significantly influences the variation in the thickness of a zinc coat on wire after the drawing process, while the factors decisive to the zinc coat thickness in the drawing process include also the total reduction. With the increase in total reduction, the zinc mass decreases, which can be associated with the elongation of the wire and stripping of the zinc coat in the approach and sizing portions of the die. The rate of these changes depend on the drawing angle. With increasing total reduction, the differences in zinc coat thickness on the surface of wires drawn at an angle of α = 3, 4, 5, 6, 7°, respectively, increase, amounting to 11.7% in draw no. 7 (G_c = 84%). In the case of drawing wires of medium- and high-carbon steels, the wire is required to have high tensile strength. Therefore, in industrial practice, galvanized wire is very often drawn with total reductions of up to 90%. Hence, to obtain a zinc coat with a specified thickness in multi-stage drawing of galvanized steel wire, it is necessary to apply optimal values of drawing angle. In addition to the zinc coat thickness specified by the standard, which is dependent on the wire diameter, the wire is also required to have high mechanical properties.

5. Testing for mechanical and engineering properties

Tests for the mechanical and engineering properties of the wire were performed in accordance with standard PN-EN 10218-1:2012 on a Zwick/Z100 testing machine and on a wire twisting and bending test device. Wires of a diameter of 2.2 mm were subjected to testing to determine the yield strength, $R_{0,2}$; tensile strength, R_m; uniform elongation, A_r; total elongation, A_c; reduction of area, *Z*; the number of twists, N_t; and the number of bends, N_b.

According to the standard, during the torsion test, specimens with dimensions of 100 × d (d – 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 ϕ 20 mm. The results of the mechanical and engineering tests are represented in Figures 6-12.

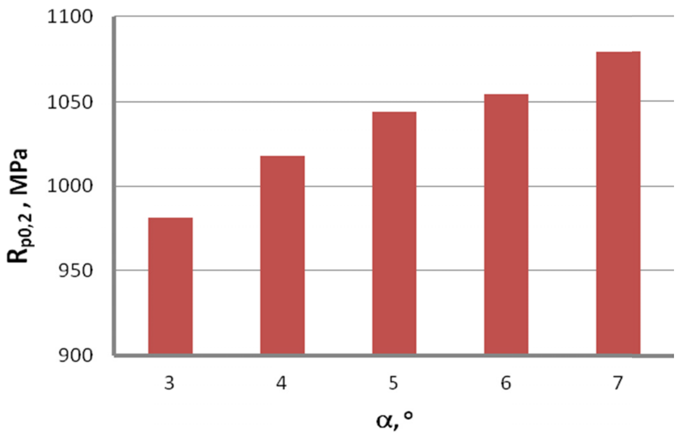

Fig. 6. Variation in yield point, $R_{p0,2}$, as a function of drawing angle α

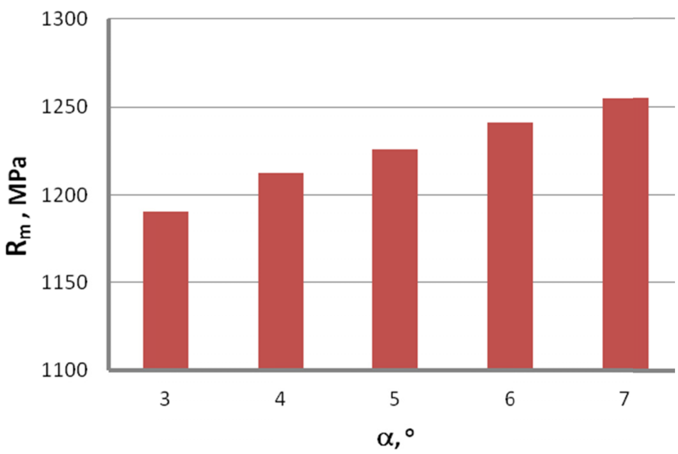

Fig. 7. Variation in ultimate tensile strength, R_m, as a function of drawing angle α

From the testing results shown in Figures 6 and 7 it can be found that the drawing angle has a marked influence on the mechanical properties of galvanized wire of medium-carbon steel. Wires drawn in dies of an angle of α = 7° were distinguished by a yield point higher by 10% and tensile strength higher by 5.4%, compared to wires drawn in dies with an angle of α = 3°. The higher values of $R_{p0,2}$ and R_m of wires drawn at large drawing angles suggest the occurrence of larger redundant strains in the drawing process, which causes an added strain hardening of the wire and an impairment of its plastic properties, as confirmed by the results presented in Figures 8-10.

The data in Figures 8-10 shows that the drawing angle influences the plastic properties of wire to a much greater extent than it does the mechanical properties. Wires drawn in dies of an angle of α = 7° were distinguished by uniform elongation and total elongation values smaller by 4.9 and 10%, respectively, and by a reduction in area smaller by 16.5%, compared to wires drawn in dies with the angle α = 3°. The poorer plastic properties of wires drawn with large drawing angle values should also

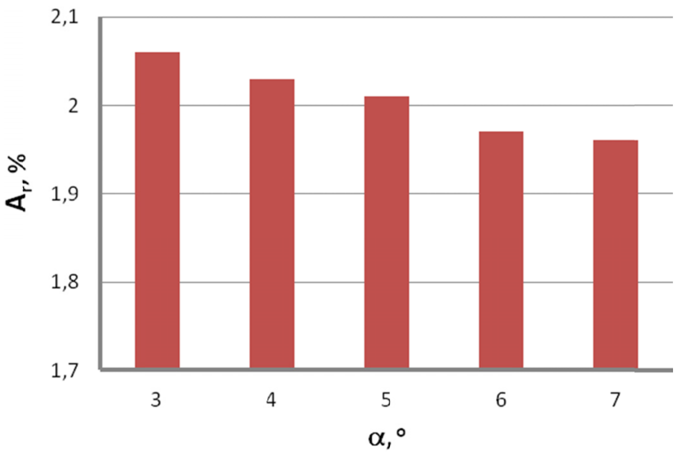

Fig. 8. Variation in uniform elongation, A_r, as a function of drawing angle α

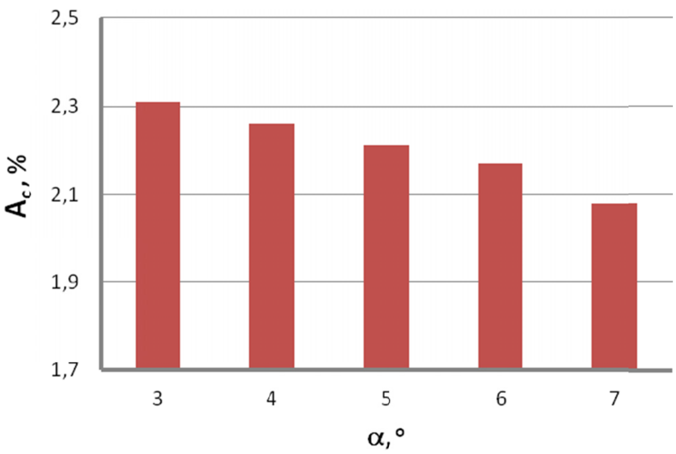

Fig. 9. Variation in total elongation, A_c, as a function of drawing angle α

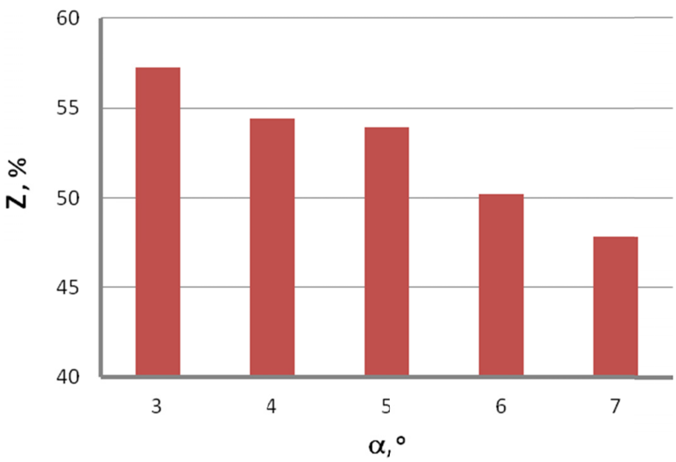

Fig. 10. Variation in the reduction of area, Z, as a function of drawing angle α

be associated also with the poorer drawing conditions for these variants. Namely, the smaller quantity of lubricant separating the wire and die surfaces in friction increased the deformation resistance, which contributed to an increase in strain intensity.

Basic tests used in industry for the qualitative assessment of steel wire, in addition to mechanical tests, are engineering tests whereby the number of twists and the number of bends are determined for the wire. The performed tests show clearly that the drawing angle strongly influences the engineering properties of wire, Figures 11-12.

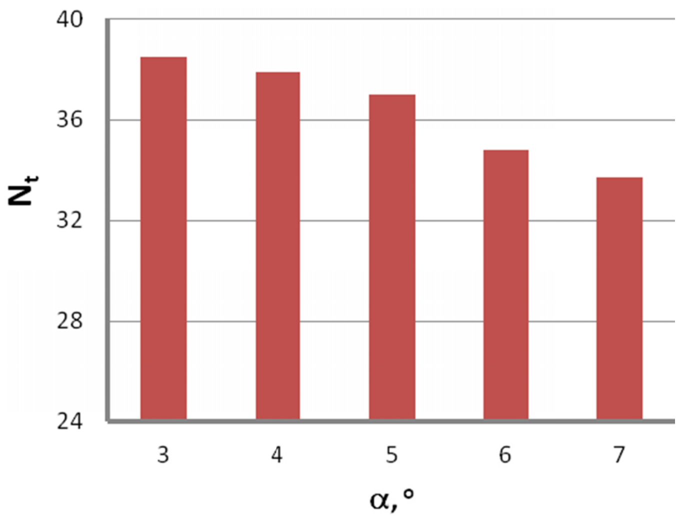

Fig. 11. Variation in the number of twists, N_t, as a function of drawing angle α

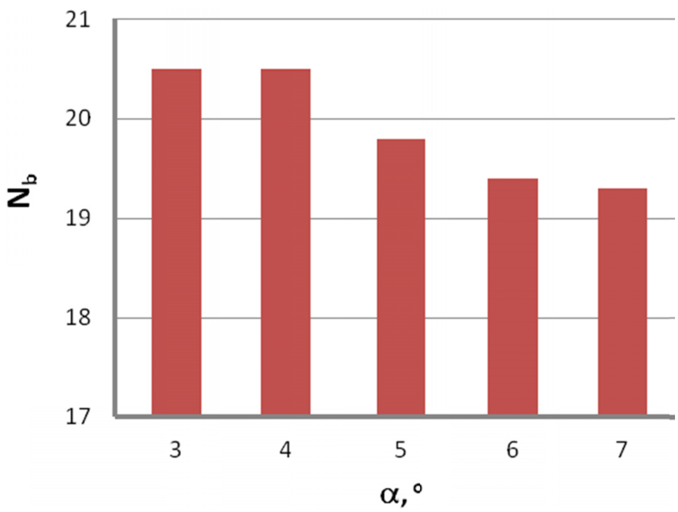

Fig. 12. Variation in the number of bends, N_b, as a function of drawing angle α

Using large drawing angles cause a decrease in the number of twists and the number of bends. Wires drawn in dies of an angle of $\alpha = 7°$ exhibited the number of twists smaller by 12.5% and the number of bends smaller by 5.9%, compared to wires drawn in dies with an angle of $\alpha = 3°$. The poorer engineering properties of wire drawn with large angles should be clearly associated with their higher deformation inhomogeneity and larger redundant strain, as confirmed by the greater strain hardening of the wire (higher yield point and ultimate tensile strength). The added strain hardening of the wire in its surface layer caused significant differences in plastic properties between individual wire layers, resulting in a reduction of its torsional and bending strength.

5. Conclusions

1. The value of die working portion angle has a significant effect on the lubrication conditions in the drawing process. The improvement of lubrication conditions for wires drawn at small angles is to be sought in smaller wire loads in the die, among other factors. This creates more advantageous conditions for lubricant spreading in the drawing process.
2. The thickness of the zinc coat in the process of drawing galvanized steel wire depends on the drawing angle, whereas, the larger the total reduction values, the greater the differences between the drawing variants under consideration.
3. In the multi-stage drawing process, the drawing angle has a fundamental effect on the mechanical properties of galvanised medium-carbon steel wire. Higher yield point and ultimate tensile strength values for wires drawn with the drawing angle ($\alpha = 7°$) should be linked with the poorer lubrication conditions and higher tangential stresses at the wire/die interface for this variant, which resulted in an increase in redundant strains and the total strain hardening of the wire. As a consequence, the above wires exhibit much poorer plastic properties; this is confirmed by lower values of both uniform and total elongation and the reduction of area.
4. Using large drawing angles cause a decrease in the number of twists and the number of bends. Wires drawn at a drawing speed of 10 m/s in dies of an angle of $\alpha = 7°$ showed the number of twists smaller by 12.5% and the number of bends smaller by 5.9%, compared to wires drawn in dies with the angle $\alpha = 3°$. The poorer engineering properties of wires drawn with large angles should be explicitly associated with their greater deformation inhomogeneity.

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