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Impact of Welding Wire Nickel Plating Process Parameters on Ni Layer Thickness

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***Abstract*—**The article presents part of research on the development of nickel plated welding wire production technology, whose application will enable the elimination of the flaws of currently manufactured welding wires. The nickel plated welding wire will be distinguished by high quality, because the Ni layer which is deposited electrochemically onto it from acid baths is characterized by very good adhesion to the steel wire surface, while the ductile nickel well deforms plastically in the drawing process and the adhesion of the Ni layer increases in the drawing process due to the occurring process of diffusion between the Ni and the steel. The Ni layer obtained in the proposed technology, despite a smaller thickness than when the wire is coated with copper, is continuous and tight, thus ensuring high corrosion resistance, as well as unsusceptible to scaling, which should provide a product that meets requirements imposed by the market. The product will also reduce, to some extent, the amount of copper brought in to steel through recycling, while the wire coating nickel introduced to the weld in the welding process is expected, to a degree, to favorably influence its mechanical properties. The paper describes the tests of the process of nickel plating of ϕ1.96 mm-diameter wires using various nickel plating baths with different process parameters.

***Keywords*—**Steel wire, plating baths, welding process, coatings.

I. Introduction

NICKEL coats are among the most common coatings, especially decorative and protecting ones. Such wide application of nickel coatings is due to their adequate corrosion resistance under normal weather conditions, easy surface treatment, etc. Nickel resistance to many acids and atmospheric factors is due to its ability to coat its own oxide layer. In spite of being more electropositive than iron, nickel has found application as a protection of steel against corrosion.

A great number of baths with varying compositions, being dependent on many factors, such as the substrate type, deposition rate, hardness and coated layer thickness, are usable industrially [1]-[4].

The most widespread types of nickel electroplating bath are the Watts baths. The Watts bath can be, either: Sulphate types – where the bath components are nickel sulphate, nickel(II) chloride and boric acid. Their composition may vary in a wide range, being determined by operating temperature, acidity (pH), or bath efficiency. Just like in the copper electroplating process, the increased bath nickel ion content in the nickel electroplating process allows higher current densities to be used. Or chloride types – which contain nickel(II) chloride and hydrochloric acid (HCl) in place of sulphuric acid. Coatings obtained from these electrolytes are fine-crystalline, but little ductile. Moreover, the Watts baths can be divided into solutions used for depositing matt coatings, operating at low current densities (below A/dcm^2, being seldom used at present), and those operating at high current densities, which are used for depositing bright coatings [5]-[8]..

Beside the Watts baths, fluoroborate and amide sulfonate baths are also in use; however, due to the costs of their components, as well and their aggressiveness (fluoroborate baths), they are used exclusively for special purposes [5]-[8].

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II. Results

A. Testing of the ϕ1.96 mm-Diameter Wire Nickel Plating Process Using Various Nickel Plating Baths with Different Process Parameters

The process of continuous welding wire nickel plating under industrial conditions has technical limitations and preconditions that are imposed by the wet drawing technology and the necessary output.

Wires of a diameter of approx. 2.00 mm were subjected to nickel plating prior to the process of "wet" drawing into a final diameter of 1.20, 1.00 and 0.80 mm, respectively. At the drawing speed after the last wet-drawing machine deformation stage set for the demonstration line at v_c = 6.0 m/s, the wire speed at entry to the first drawing stage will be different for individual final wire diameters (Table I).

TABLE I
Wire Speeds before the First "Wet" Drawing Stage as Dependent on the End Wire Diameter

Starting wire diameter, mm	End final wire diameter, mm	Wire v_c at the wet-drawing machine entry, m/s	Wire v_c after the last drawing stage, m/s
ϕ1.96	1.20	2.25	6.0
	1.00	1.56	
	0.80	1.00	

At so high wire velocities at the entry to the wet-drawing machine, there is a necessity to minimize the nickel plating duration (so that the nickel plating plant does not have too large overall dimensions), while maintaining the adequate thickness and tightness of the Ni coating on the final wire to ensure its high corrosion resistance.

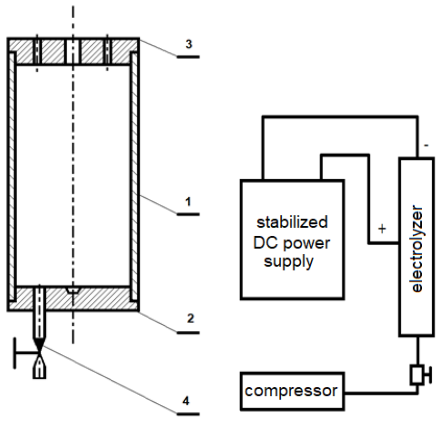
For testing the welding wire nickel electroplating process, 3

types of electrolyte were used, with compositions and parameters shown in Table II.

TABLE II
CHEMICAL COMPOSITIONS AND OPERATION PARAMETERS OF THE NICKEL PLATING BATH

Components	Bath type		
	A	B	C
	Sulphate bath		Chloride bath
	Watts bath	High-chloride bath	
Nickel sulphate, $NiSO_4$ $7H_2O$, g/l	300	300	-
Nickel chloride, $NiCl_2$ $6H_2O$, g/l	30	90	250
Boric acid, H_3BO_3, g/l	30	30	30
Process conditions			
pH	4.11	3.83	3.03
Optimal operating temperature, °C	35-70	35-70	40-60
Optimal cathodic current density, A/dm^2	1.08-6.46	1.08-6.46	5.38-10.75
Anodes	Ni	Ni	Ni
Anode-to-cathode surface area ratio	1:1	1:1	1:1
Cathodic efficiency, %	95-100	95-100	90-100
Stirring at the cathode:			
Intensive	+	+	+
With compressed air		+	+

The process of deposition of the Ni coating from electrolytes onto cleaned 1.96 mm-diameter wires was carried out on a test stand, as shown in Fig. 1.



(a) (b)

Fig. 1 Schematic diagram of the test stand for the electrochemical deposition of nickel coatings; (a) electrolyzer cross-section, (b) the system's schematic diagram; 1-tubular Ni anode, 2-non-conducting bottom, 3-non-conducting upper cover, 4-air inlet

The thickness of the wire Ni layer was determined by a gravimetric method, assuming the specific weight D = 8.99 g/cm^3; while when determining the process efficiency, the electrochemical coefficient for Ni was adopted as k = 1.095 g/A h.

Due to the preconditions discussed above, the nickel plating duration in the tests was reduced to max. 30 s, while focusing in particular on the acceptable (due to the nickel plating tan dimensions) duration of 10 s by attaching more weight to varying the current density, i.e. a readily changeable process parameter that has (just as nickel plating duration) a directly proportional effect on the Ni coating thickness.

Table III and Fig. 2 show variation in the thickness of the Ni layer deposited from the A-type bath as a function of nickel plating duration.

TABLE III
VARIATION IN NI COATING THICKNESS AS A FUNCTION OF THE DURATION OF NICKEL PLATING IN THE WATTS BATH, J = 4 A/DM^2, T = 20 °C

No.	Nickel plating duration s	Nickel plating current density A/dm^2	Average quantity of Ni on samples g	Ni coating thickness µm	Process efficiency %
1	5	4	0.00120	0.059	86.56
2	10	4	0.00244	0.120	88.01
3	30	4	0.00751	0.367	90.31
4	20	4	0.00495	0.242	89.29

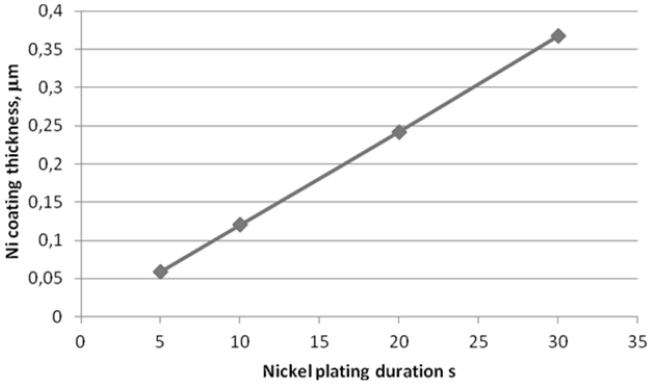


Fig. 2 Variation in Ni coating thickness as a function of nickel plating duration, T = 20 °C, J = 4 A/dm^2

It was found that the variation in Ni coating thickness as a function of nickel plating duration showed practically a linear behaviour and with the increase in nickel plating duration, the process efficiency slightly increased.

Further tests determined the variation in Ni coating thickness as a function of nickel plating current density for different nickel plating bath types (Table IV and Fig. 3).

TABLE IV
VARIATION IN NI COATING THICKNESS AS A FUNCTION OF THE CURRENT DENSITY OF NICKEL PLATING IN DIFFERENT BATH TYPES, T = 10 S, T = 20 °C

No.	Bath type	Nickel plating duration s	Nickel plating current density A/dm^2	Average quantity of Ni on samples g	Ni coating thickness µm	Process efficiency %
1	A	10	4	0.00244	0.120	88.01
2	A	10	8	0.00490	0.255	88.37
3	A	10	12	0.00741	0.362	89.10
1	B	10	8	0.00527	0.274	95.05
2	B	10	12	0.00799	0.390	96.07
1	C	10	8	0.00535	0.278	96.49
2	C	10	12	0.00810	0.395	97.41

From the test results shown above, a slight increase in Ni coating thickness obtained from electrolytes B and C, compared to electrolyte A, can be found, which might be due

to the higher efficiency of the process in those electrolytes, resulting from their lower pH (see Table II). The electrolyte of type A is, however, the cheapest by virtue of the lowest content of the expensive nickel chloride in its chemical composition, which should fully compensate for the losses due to the lower process efficiency.

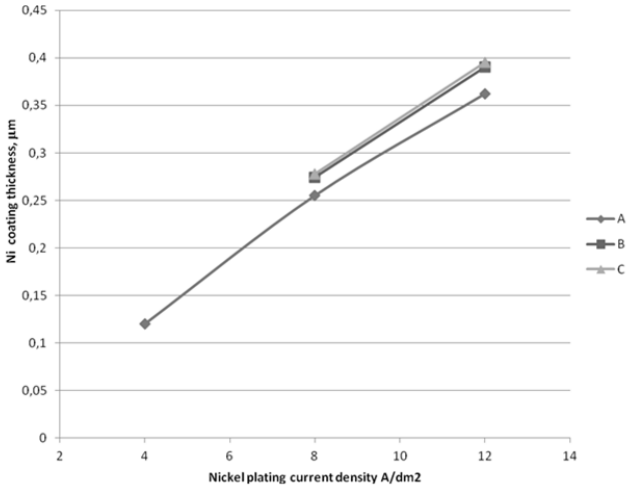


Fig. 3 Variation in Ni coating thickness as a function of nickel plating current density, T = 20 ºC, t = 10s, for different bath types

When designing the elements of the demonstration line for wire nickel plating it was necessary to determine the value of nickel plating current (per 1 m of the wire to be coated), which is influenced by the process efficiency. Table V and Fig. 4 show the influence of process efficiency on the actual value of the current of nickel plating in the A-type electrolyte.

The tests enabled a more accurate selection of the stabilized DC power supply with the assumed length of wire subjected to nickel plating process.

The next tests were intended to determine the effect of the temperature and intensive stirring of the A-type bath on the Ni coating thickness as a function of nickel plating current and duration (Table VI, Figs. 5 and 6).

From the tests presented below it can be concluded that a higher temperature of the bath and its intensive stirring both contribute to an increase in deposited Ni thickness in the range of 8÷10% through an increase in process efficiency that might be caused by a better transfer of ions in the bath.

TABLE V
THE INFLUENCE OF PROCESS EFFICIENCY ON THE ACTUAL VALUE OF THE CURRENT OF NICKEL PLATING IN ELECTROLYTE OF TYPE A

No.	Theoretical nickel plating current density A/dm^2	The theoretical magnitude of nickel plating current per 1 m of ϕ1.96 mm-diameter wire A/m	Process efficiency %	The actual magnitude of nickel plating current per 1 m of ϕ1.96 mm-diameter wire A/m
1	4	2.46	88.01	2.80
2	8	4.93	88.37	5.58
3	12	7.39	89.10	8.29

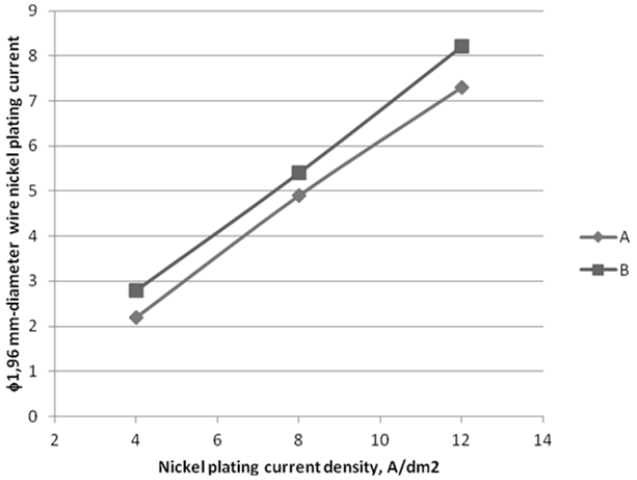


Fig. 4 The effect of process efficiency on the magnitude of actual ϕ1.96 mm-diameter wire nickel plating current; A-theoretical magnitude of nickel plating current, A/m of wire, B- magnitude of nickel plating current allowing for process efficiency, A/m of wire

As the differences in Ni coating thickness obtained for different values of time t and current density J are similar, a diagram of the thickness of the Ni coating of 1.96 mm-diameter wires as a function of the product of current density and nickel plating time (Jxt) was plotted for all variants of the process of nickel plating in the A-type electrolyte (Fig. 7).

TABLE VI
THE EFFECT OF THE TEMPERATURE AND INTENSIVE STIRRING OF THE NICKEL PLATING BATH ON THE NI COATING THICKNESS AS A FUNCTION OF NICKEL PLATING CURRENT AND DURATION

No.	Ni plating duration s	Ni plating current density A/dm^2	Aver. quantity of Ni on samples g	Ni coat. thickn. µm	Process eff. %	Aver. quant. of Ni on samples g	Ni coating thickn. µm	Process eff. %
			T=20°C, with no solution stirring			T=20°C, intensive solution stirring		
1	10	4	0.00244	0.120	88.01	0.00267	0.131	96.33
2	10	8	0.00490	0.255	88.37	0.00535	0.278	96.49
3	10	12	0.00741	0.362	89.10	0.00805	0.393	96.79
4	10	12	0.01595	0.779	95.90	0.01677	0.819	99.19

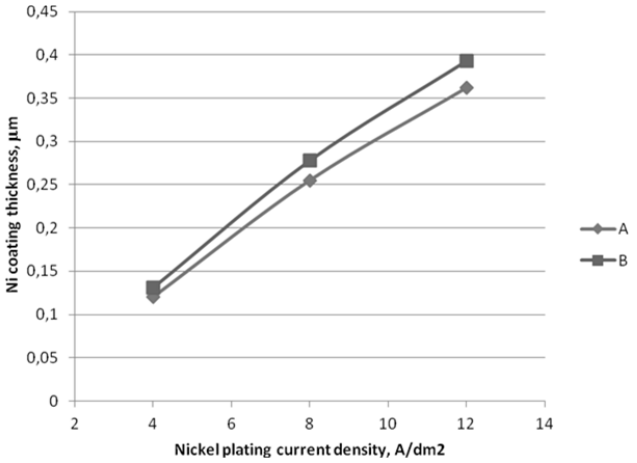


Fig. 5 The effect of temperature and intensive stirring on the Ni coating thickness, A- without solution stirring, T = 20 °C, t = 10s B- intensive solution stirring, T = 45 °C, t = 10s

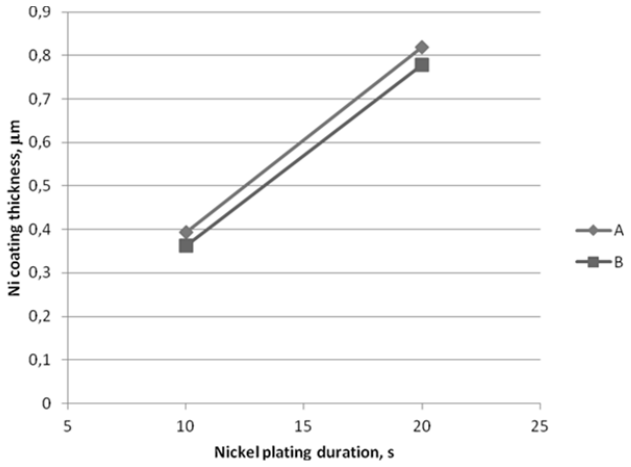


Fig. 6 The effect of temperature, intensive stirring and nickel plating duration on the Ni coating thickness, A- without solution stirring, T = 20 °C, J = 12 A/dm^2; B- intensive solution stirring, T = 45 °C, J = 12 A/dm^2

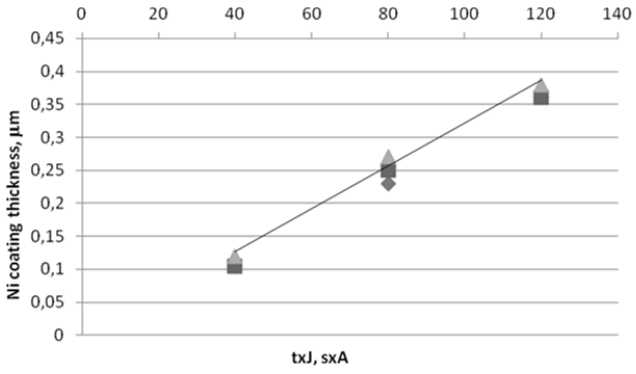


Fig. 7 Variation of Ni coating thickness as a function of the product of current density J and nickel plating time t for different values of these parameters

By using the diagram shown in Fig. 7, it is possible, for the assumed Ni coating thickness, to determine the value of the product Jxt, and then to determine the nickel plating current density J for a specific time t of wire residence in the bath. These relationships should be helpful in the design of the electrolyzer in the demonstration line.

B. Testing the Process of Drawing ϕ1.96 mm-Diameter Wires Nickel Plated in Different Nickel Plating Baths with Different Process Parameters

Intermediate ϕ1.96 mm-diameter wires were electroplated with a Ni layer in electrolytes of type A, B, and C, respectively, with different values of current density and nickel plating time.

Designations of variants for different values of t [s] x J [A] are shown in Table VII.

TABLE VII
THE PARAMETERS OF THE PROCESS OF NICKEL PLATING OF ϕ1.96 MM-DIAMETER WIRES IN DIFFERENT TYPES OF ELECTROLYTE

Electrolyte type	Nickel plating variant designation	Nickel plating parameters txJ, sxA
A	1	5x4
A	2	10x4
A	3	10x8
A	4	10x12
B	7	10x8
B	8	10x12
C	12	10x8
C	13	10x12

On account of the fact that all electrolyte types have high acidity, that is they are able, to some extent, to clean the wire surface from grease, uncleaned wires from two drawing variants (W3 and W6), on which the amount of grease after the "dry" drawing process was the smallest, were nickel plated.

Designations of variants for different values of txJ and different electrolytes are shown in Table VIII.

TABLE VIII
THE PARAMETERS OF THE PROCESS OF NICKEL PLATING OF ϕ1.96 MM-DIAMETER INTERMEDIATE WIRES UNCLEANED FROM GREASE IN DIFFERENT TYPES OF ELECTROLYTE

Electrolyte type	Nickel plating variant designation	Wire drawing variant	Nickel plating parameters txJ, sxA
A	5	W3	10x8
A	6	W6	10x8
B	9	W3	10x8
B	10	W6	10x8
B	11	W6	10x12
C	14	W3	10x8
C	15	W6	10x8

Wires from all nickel plating variants (both cleaned and uncleaned from grease) were drawn into a final diameter of 1.00 mm, and some of them, into a diameter of 0.79 mm. A draw distribution identical to the one that would be applied in the wet-drawing machine drawing process in an industrial plant was used.

A drawing scheme and the values of single and total cross-section reductions are shown in Table IX.

TABLE IX
DISTRIBUTION OF DRAWS AND THE SINGLE AND TOTAL VALUES OF WIRE CROSS-SECTION REDUCTIONS, G_p,% AND G_c,%

Draw no.	Wire diam., mm	G_p, %	G_c, %
0	1.96	-	-
1	1.91	5.04	5.04
2	1.75	16.05	20.28
3	1.56	20.54	36.65
4	1.43	15.97	46.77
5	1.29	18.62	56.68
6	1.17	17.74	64.37
7	1.05	19.46	71.30
8	0.97	14.66	75.51
9	0.88	18.00	79.84
10	0.79	19.41	83.75

By making calculations for different nickel plating variants, the thickness of the nickel coating on ϕ1.96 mm-diameter wires and on final ϕ1.20, ϕ1.00 mm and ϕ0.80 mm-diameter wires was determined. The results are shown in Table X and Fig. 8.

TABLE X
THE THICKNESS OF THE NI COATING ON ϕ1.96 MM-DIAMETER WIRES AND ON FINAL WIRES FOR DIFFERENT VARIANTS OF NICKEL PLATING IN THE A-TYPE ELECTROLYTE

Nickel plating parameters	Nickel plating parameters txJ, sxA	Wire diameter, mm			
		1.96	1.20	1.00	0.80
		Ni coating thickness, μm			
2	10x4	0.120	0.073	0.061	0.049
3	10x8	0.255	0.156	0.130	0.104
4	10x12	0.362	0.222	0.158	0.148

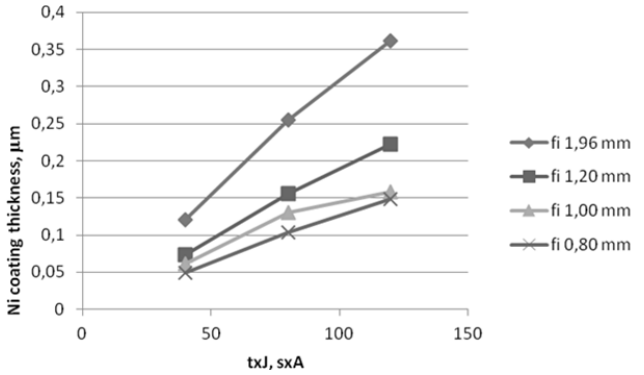


Fig. 8 Variation in Ni coating thickness as a function of txJ for different ϕ1.96 mm-diameter wires and different final diameters

The diagram shown in Fig. 8 can be used for determining the value of txJ [sxA] needed for obtaining the assumed thickness of the Ni coating on final wires of varying diameters.

For final ϕ1.00 mm-diameter wires coated with a Ni layer in different types of electrolyte with different process parameters, nickel coating adhesion tests were performed by three methods, namely:

1. The winding method, whereby the wire is wound onto a round core of a diameter equal to four diameters of the wire being wound. The absence of cracks and delaminations was considered as good adhesion of the coating.
2. The friction method consisting in fast rubbing of the coating with polished steel and copper bars. If no blisters appeared within 10 seconds, then the adhesion was considered to be good.
3. The "engineering bending" method according to standard PN–80013. The results were considered good, if the electroplated layer near the fracture did not show any delaminations or losses.

Test results for 10 samples for each method and each variant are shown in Table XI.

TABLE XI
THE RESULTS OF THE TESTS OF NI COATING ADHESION TO THE WIRE SURFACE

Electrolyte type	Nickel plating variant designation	Nickel plating parameters txJ, sxA	Number of positive tests, %		
			Testing method		
			Winding method	Friction method	Bending method
A	2	10x4	100	100	100
A	3	10x8	100	100	100
A	4	10x12	100	100	90
B	7	10x8	100	100	100
B	8	10x12	100	100	90
A	6	10x8	100	90	80
B	9	10x8	100	80	60

III. SUMMARY

The nickel plating process tests carried out for three electrolytes have shown that electrolytes B and C have a process efficiency higher by approx. 8% compared to the classical Watts electrolyte (electrolyte A); however, we recommend electrolyte A for commercial use in the nickel plating process, because of the lower price of its components.

The price of nickel chloride is several times higher than that of nickel sulphate. The electrolyte of type B contains 3 times more $NiCl_2$, and the electrolyte of type C as much as 8 times more $NiCl_2$ per 1 litre of solution. The difference in the price of the components will surely compensate for a little higher energy consumption due to the lower process efficiency.

The nickel electroplating plant is expected to ensure the deposition of the appropriate thickness of the Ni coating onto ϕ1.96 mm-diameter wire moving through the plant at a linear speed from 1.00 to 2.25 m/s (Table I), depending on the diameter of final wire obtained from "wet" drawing.

The speed at which wire is "picked up" by the wet-drawing machine determines the duration of plating the wire in the electrolyzer, which translates into the thickness of the deposited Ni coating. The thickness of the deposited Ni coating can be controlled within a certain range by increasing the magnitude of nickel plating current density.

For the proposed electrolyte, it is recommended to use current densities ranging from the optimum of 4 A/dm^2 to the maximum of 12 A/dm^2. Upon the analysis of the data shown in Table X and in Fig. 3, the following assumptions necessary for the design of a nickel plating plant are proposed:

- 3÷5 passes of wire through the nickel plating baths,
- the "active" length of wire between successive rollers of

2÷3 m, which makes a wire length in the bath of 6÷15 m, thus enabling nickel plating of wire taken up at a speed of v = 1.00 m/s for a duration of 6 ÷ 15 s, while wire taken up at a speed of v = 2.25 m/s, for a duration of 2.7 ÷ 6.7 s.

This range of nickel plating times provides the capability to control Ni coating thickness in a wide range for all wire "pick-up" speeds.

Based on the data provided in Table X it can be stated that, with the nickel plating parameters t x J = 10 x 4 = 40 [sxA], a sufficient Ni coating thickness can be obtained on final 1.20 ÷ 0.80 mm-diameter wires; therefore, e.g. with an "active" wire length of 3m for wire "picked up" at v = 1.0 m/s (final ϕ0.80 mm-diameter wire), three passes through the electrolyte (time 9s) will suffice; so, in order to meet the condition t x J = 40 [sxA], the current density at the 88.37% process efficiency should be approx. 5.1 A/dm^2.

For wire taken up at v = 1.56 m/s (final ϕ1.00 mm-diameter wire), the time of passing through the electrolyte will be 5.77 s, so the necessary current density allowing for the efficiency will amount to 7.9 A/dm^2. For wire taken up at v = 2.25 m/s, the process parameters will be the following: t = 42, J = 11.33 A/dm^2.

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