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EFFECT OF HISTORY OF DEFORMATION AND HEAT TREATMENT ON COLD DRAWING PROCESS PARAMETERS AND FINAL PROPERTIES OF AISI 302 STAINLESS STEEL WIRE

The paper focuses on the investigation of AISI 302 steel wire of different initial diameters, in solutionized condition. Three different drawing schedules were realized, starting from three different diameters, where two smaller-gauge wires were obtained by drawing of large-diameter wire and applying solution heat treatment to the product. However, the drawing schedules were carried out with almost the same total reduction and similar partial reductions. The measurement of drawing force was performed for each drawing pass, and the samples of wire were taken after each pass. The samples were then tested to obtain a set of mechanical and technological properties, as well as the distribution of Vickers hardness on wire cross section. Finally, the effect of different history of deformation and heat treatment on drawing process stability and final properties of drawn wires was discussed.

Keywords: Wire drawing; stainless steel; history of deformation; mechanical properties; hardness

1. Introduction

The modern engineering creates the need to produce materials meeting a variety of high requirements, such as specified mechanical and physical properties, corrosion resistance, dimensional tolerances, limited weight, as well as high functional quality and aesthetic appearance. One of many examples may be a high demand for light-gauge products of stainless and acid-resistant steels, destined for manufacturing of springs and other products showing extremely high fatigue strength [5,6,12,13,17,18]. The proper design of technologies of deep processing of specialty steels requires the knowledge of interdependent mechanical and structural phenomena occurring in these steels under heavy plastic deformation [7,19]. The significance of the evolution of microstructure, texture and phase composition in heavily deformed products has to be emphasized [1-4,9-11,14-16,20,21,23-25]. The possible formation of strain-induced martensite has a strong impact on material's properties. The other important factor influencing the strain hardening character of a material being deformed is the strain redundancy. The redundant work has to be taken into account in the analysis of material flow during drawing, as it significantly contributes to the strain inhomogeneity and resulting non-uniformity of mechanical properties of a final product [8,22,26]. The research described in the paper discusses a problem of quality of specialty steel wires, considering the influence of history of previous deformation and heat treatment operations on the character of strain hardening and the resulting final properties of wire.

2. Experimental procedure

2.1. Material

The material selected to the investigations was AISI 302 austenitic stainless steel (material no. 1.4310: X10CrNi18-8 according to EN 10088). The chemical composition of the steel being tested is given in TABLE 1. The material was supplied in a form of drawn wire of 8.5 mm diameter, in the solution annealed condition.

TABLE 1

Chemical composition of AISI 302 steel used in the investigations (wt.%)

C	Mn	Si	P	S	Cr	Ni	Mo	N
0.094	0.89	0.70	0.026	0.003	17.62	7.75	0.42	0.03

AISI 302 is a chromium-nickel austenitic steel, the grade being a modification of more common AISI 304, showing

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higher carbon content as a main difference. Often sold in strip and wire forms, grade 302 stainless steel is primarily used by the manufacturers of conical compression springs. One of this steel's main attributes is that it is resistant to solvents, acids and other corrosive chemicals. AISI 302 stainless steel is frequently found in spring form within machines used in kitchens, food processing businesses, medical settings and dairies. There are instances, such as in temper rolled products, when type 302 is preferred over type 304 since the higher carbon permits meeting of yield and tensile strength requirements while maintaining a higher level of ductility (elongation) versus that of the lower carbon type 304.

2.2. Drawing process

The experiment consisted of two drawing stages. The first stage was the preparation of wires of three different diameters, which were then used in the second drawing stage. The initial wire of 8.5 mm diameter was drawn to the diameter of 5.5 mm and then solution annealed. Subsequently, the wire of 5.5 mm diameter was drawn to the diameter of 2.97 mm, also with subsequent solution annealing. The heat treatment of wires was performed at the temperature of 1100°C, with 30 min holding time and following water quenching. Three drawing schedules were designed as follows, assuming almost identical total deformation and similar partial reductions:

Schedule A (total reduction: 52.6%)

$$\text{Ø } 8.5 \xrightarrow{15.8\%} \text{Ø } 7.8 \xrightarrow{5.8\%} \text{Ø } 7.57 \xrightarrow{15.5\%} \text{Ø } 7.0$$

$$\xrightarrow{13.8\%} \text{Ø } 6.5 \xrightarrow{19\%} \text{Ø } 5.85 \text{ mm}$$

Schedule B (total reduction: 52.3%)

$$\text{Ø } 5.5 \xrightarrow{17.4\%} \text{Ø } 5.0 \xrightarrow{7.8\%} \text{Ø } 4.8 \xrightarrow{12.1\%} \text{Ø } 4.5$$

$$\xrightarrow{20.6\%} \text{Ø } 4.01 \xrightarrow{10.2\%} \text{Ø } 3.8 \text{ mm}$$

Schedule C (total reduction: 56.4%)

$$\text{Ø } 2.97 \xrightarrow{17.4\%} \text{Ø } 2.7 \xrightarrow{12.9\%} \text{Ø } 2.52 \xrightarrow{9.3\%} \text{Ø } 2.4$$

$$\xrightarrow{16\%} \text{Ø } 2.2 \xrightarrow{20.6\%} \text{Ø } 1.96 \text{ mm}$$

In case of the schedule A, the realization of the last drawing pass (Ø 6.5 → Ø 5.85) failed. When attempted to be drawn, the wire breaking occurred, which was evidently caused by the depletion of plasticity margin. The drawing experiments were realized with application of chain drawbench using sintered carbide dies of 12° die angle, drawing velocity of 0.1 m/s and sodium soap powder as a lubricant. The drawing force was measured and registered for each drawing pass as a function of time, in order to give information about the process stability. The results obtained for each drawing schedule are presented in Fig. 1. In case of the schedule C, only selected passes are presented in order to avoid excessive overlapping of the individual curves.

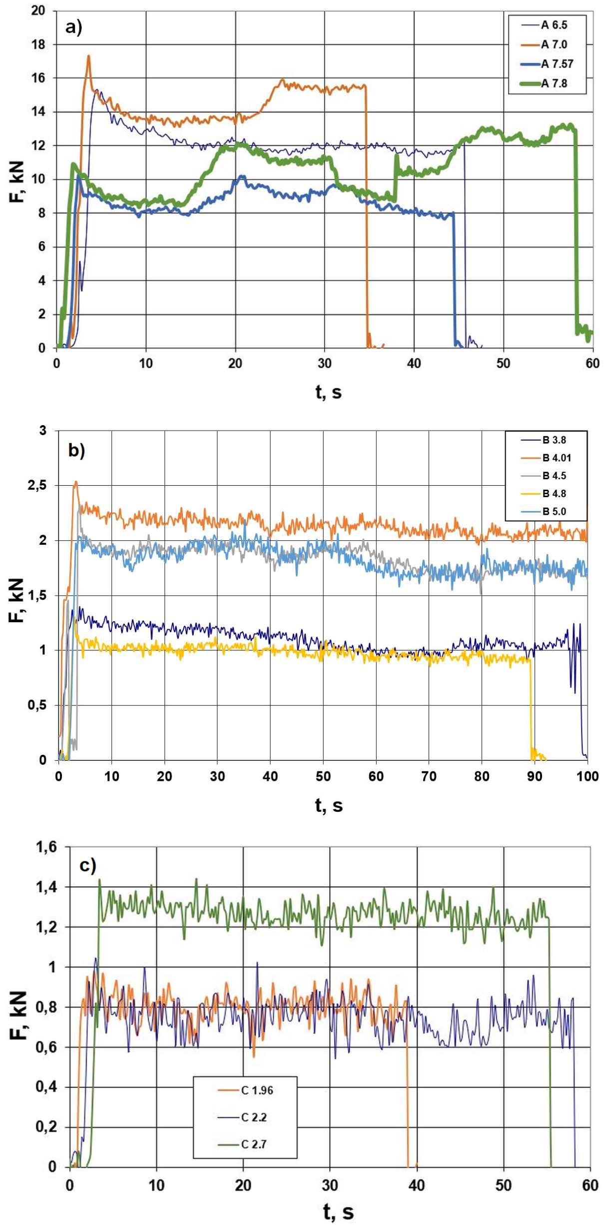

Fig. 1. Variations of drawing force observed in consecutive passes (wire diameters are indicated) in schedule A (a), B (b) and C (c)

3. Results

3.1. Mechanical testing

The initial wires as well as wire specimens taken after each drawing pass were subjected to mechanical testing with application of Instron 1196 and Instron 4502 testing machines (Fig. 2) and hand-operated device used for multiple bending test (Fig. 3). The changes of tensile strength (R_m), yield strength ($R_{p0,2}$), elongation (A_{100}), reduction of area at fracture (Z) and number of bends till fracture (L_p) were investigated as a function of total reduction. The obtained results are given in TABLE 2 and illustrated graphically in Figs. 4-6. In case of schedule A, the number of bends was not analysed due to large wire diameter and the resulting technical difficulties.

Fig. 2. Instron 1196 (a) and Instron 4502 (b) testing machines used to perform tensile test of wire specimens

Fig. 3. Multiple bending device used to evaluate the number of bends till fracture

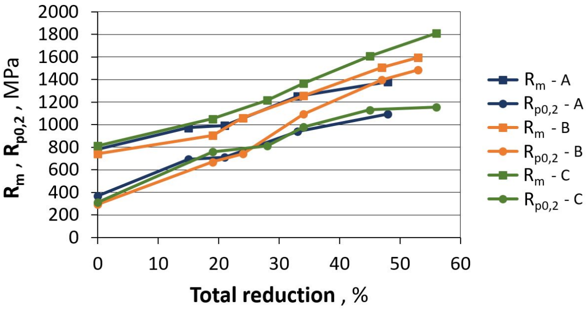

Fig. 4. Tensile strength and yield strength as a function of total reduction when drawing AISI 302 steel wire according to different drawing schedules

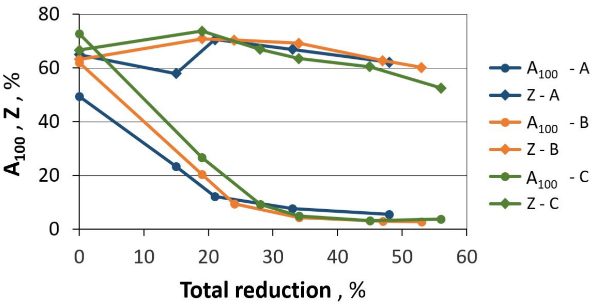

Fig. 5. Elongation and reduction of area at fracture as a function of total reduction when drawing AISI 302 steel wire according to different drawing schedules

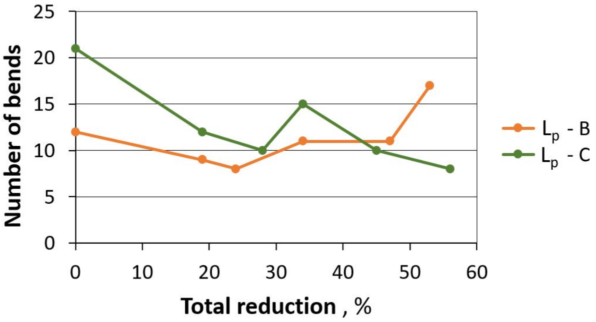

Fig. 6. Number of bends till fracture as a function of total reduction when drawing AISI 302 steel wire according to different drawing schedules

3.2. Hardness testing

The measurements of hardness distribution on cross sections of the initial wire (Fig. 7) as well as wires after each drawing pass were performed in the next stage of research work. Zwick 3212002 hardness tester was used, with application of Vickers

TABLE 2

Mechanical properties of drawn wires of AISI 302 steel (R_m – tensile strength, $R_{p0,2}$ – yield strength, A_{100} – elongation, Z – reduction of area at fracture, L_p – number of bends; *l.o.d.* – lack of data)

Drawing schedule	**Wire diameter**	R_m	$R_{p0,2}$	A_{100}	Z	L_p	**Total reduction**
	mm	**MPa**	**MPa**	**%**	**%**	**—**	**%**
A	8.5	783	371	49.5	65.0	*l.o.d.*	0
	7.8	973	692	23.3	57.9	*l.o.d.*	15.4
	7.57	994	710	25.0	70.6	*l.o.d.*	20.8
	7.0	1253	941	20.0	66.8	*l.o.d.*	32.3
	6.5	1378	1096	5.5	62.1	*l.o.d.*	41.7
	5.85	*l.o.d.*					52.6
B	5.5	743	295	62.0	63.2	12	0
	5.0	906	670	20.4	70.9	9	17.4
	4.8	1061	743	9.4	70.4	8	24.0
	4.5	1255	1094	4.3	69.2	11	33.1
	4.01	1508	1396	3.0	62.7	11	46.8
	3.8	1593	1486	2.8	60.2	17	52.3
C	2.97	815	313	72.8	66.6	21	0
	2.7	1052	761	26.7	73.7	12	17.4
	2.52	1218	813	9.3	66.9	10	28.1
	2.4	1366	978	4.9	63.5	15	34.7
	2.2	1610	1131	3.2	60.5	10	45.1
	1.96	1810	1154	3.7	52.5	8	56.4

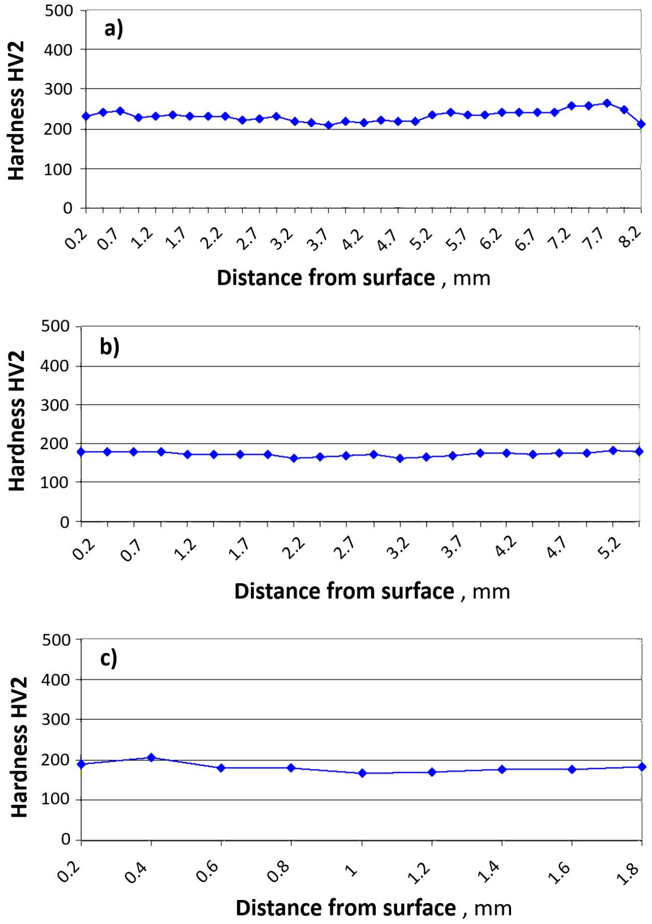

Fig. 7. Initial hardness distribution on cross sections of wires before drawing according to schedules A (a), B (b) and C (c)

method and 2 kg load. The measurements allowed to obtain the distributions of HV2 hardness along the diameter of wires being tested. The results are presented in Fig. 8, showing the final hardness level in wires after realization of different drawing schedules.

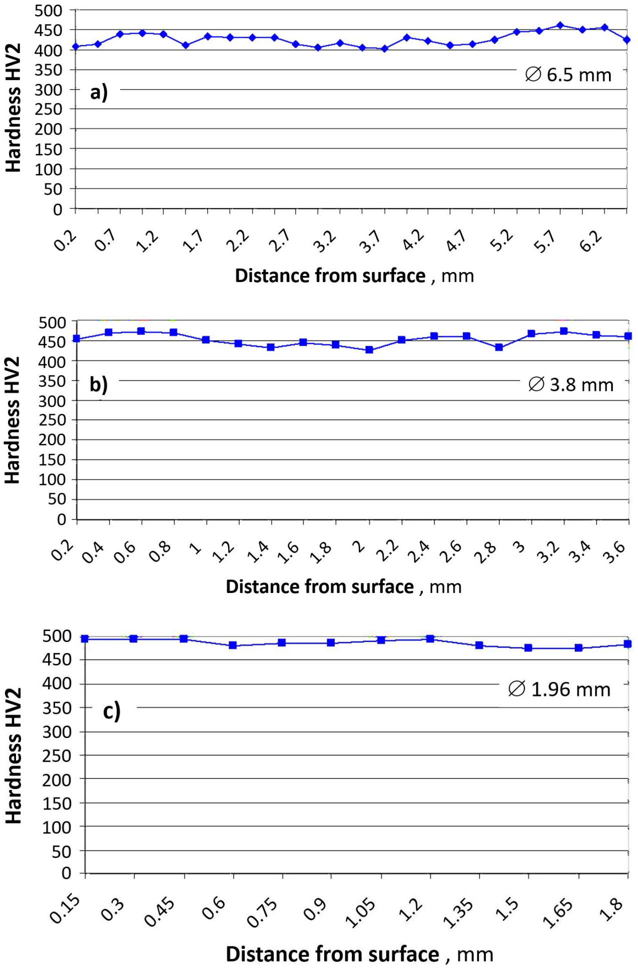

Fig. 8. Final hardness distribution on cross sections of wires drawn according to schedules A (a), B (b) and C (c)

4. Discussion

The influence of a history of deformation and heat treatment on a drawing process was investigated through the analysis of drawing force variations in the schedules A, B and C. The wire of 8.5 mm diameter was delivered in a state after solution annealing, and was used as a feedstock for two other initial wire diameters (5.5 mm and 2.97 mm). The wires of 5.5 mm and 2.97 mm diameters were also subjected to solution annealing. Thus, the obtained history of treatment of a feedstock material for individual drawing schedules was given as follows:

Schedule A (8.5 mm initial diameter):

solution annealing

Schedule B (5.5 mm initial diameter):

solution annealing → drawing
→ solution annealing

Schedule C (2.97 mm initial diameter):

solution annealing → drawing
→ solution annealing → drawing → solution annealing

The wire of 5.5 mm diameter was obtained by means of multi-stage drawing from 8.5 mm diameter, while 2.97 mm diameter wire was produced by multi-stage drawing from 5.5 mm.

The variations of a drawing force observed in the schedule A (Fig. 1a) indicate very unstable process in the run of first passes. In the succeeding passes, the drawing force variations become more and more stable, as the force levels off. The overall changes of a drawing force in first passes may result from the process of stabilization of lubrication conditions. In case of the schedule B (Fig. 1b), the drawing force remains quite stable, with a slight decrease in time, which can also be connected with improving lubrication conditions during drawing. This decrease of a drawing force in time was not observed in case of the schedule A. On the other hand, in case of the schedule B slightly higher deviation from the average was apparent. Drawing according to the schedule C (Fig. 1c) generates, overall, relatively stable drawing force, although the deviations from the average are the highest in percentage terms in this case. Such character of drawing force variations may result from higher sensitivity of force level to the changes of lubrication conditions during drawing of smaller diameter wire. When drawing wires of larger diameter, the drawing force reaches relatively high level, at which the changes of friction conditions do not result in such considerable deviations as in case of finer wires. In general, the average level of drawing force results directly from the size of wire cross section and the amount of unit reductions realized in individual passes.

The variations of strength properties (Fig. 4) illustrate quite typical strain hardening pattern resulting in uniform increase of tensile strength and yield strength. Some difference can only be seen in the character of changes of plasticity margin, i.e. the span between tensile strength and yield strength. In case of the schedule A, this parameter remains at approximately the same level within the analysed reduction range. In spite of this, the realization of the last pass in the schedule A failed, which could indicate the depletion of plasticity margin. Most likely, relatively large reduction in the last pass (19%) required to apply the drawing force that generated the stress exceeding the material's strength. In case of the schedule B, the span between tensile strength and yield strength decreases in consecutive passes, which is the most typical situation. Drawing according to the schedule C results in the reverse tendency, most clearly visible in the last pass.

The variations of plastic properties as a function of total reduction (Fig. 5) show that the reduction of area at fracture changes in a similar way in all three schedules, both quantitatively and qualitatively. Some differences and discrepancies can be only seen after first passes in the schedule A. The variations of elongation are of similar character in the schedules B and C. In case of the schedule A, the decrease of elongation after first pass is smaller, staying at about 20% in successive passes and finally dropping to a level of a few percent after the last pass.

The number of bends as a function of total reduction shows some differences in the schedules B and C (Fig. 6). The first difference is the level of this parameter shown by initial wire, with much higher value obtained in the schedule C. The other visible difference is the character of changes of this parameter in the last passes – in case of the schedule B the number of bends increases, while decreasing in the schedule C. The wires drawn according to the schedule A were not subjected to bending test, due to a large cross section of wire.

The level and the character of distribution of hardness on the cross section of wire after drawing is determined mainly by two factors – the amount of deformation and the effect of redundant work. Increasing deformation results in more intensive strain hardening, thus increasing general hardness level. The redundant strains occur as a result of shear of the material in the deformation zone. The effective strain is free from redundancy only at the axis of wire, where the material particles flow with no change of direction through the deformation zone. The occurrence of redundant strains increasing from the axis towards the wire surface results in additional strain hardening. This in turn leads to higher hardness. Consequently, the minimum hardness is expected at the wire axis, and the maximum hardness should be observed in the layers close to wire surface. The difference between these values is larger for higher die angles. Additionally, the other factors may also influence the hardness distribution on the cross section of drawn wire. One of them is a friction occurring at the interface between wire and die, which hinders the material flow in surface layers, while central layers may flow faster. In case of multi-pass drawing, there is another important problem – the drawing schedule, i.e. the distribution of unit reductions for a certain total reduction. There is a general rule stating that in order to obtain high strength of wire, lower number of larger reductions should be applied, while relatively good ductility is to be expected when higher number of smaller reductions is realized. The consecutive drawing passes can be arranged with increasing or decreasing reductions, with the reduction in the last pass being also of importance. The distribution of deformation stages in multi-pass drawing also influences the strain redundancy. Since the redundant work decreases with increasing reduction, the higher redundancy resulting in higher hardness non-uniformity should be expected when larger number of passes with smaller reductions is realized. It should be noticed that each single reduction should not fall below a certain level, which may result in the deformation limited only to surface layers ("skin pass" effect). The analysis of hardness distribution in initial wires (Fig. 7) showed that the average hardness level of wires of 5.5 mm and 2.97 mm diameter is similar (about 180 HV2). In case of wire of 8.5 mm diameter, the hardness level is higher (approx. 230 HV2). Most probably, the influence of the history of deformation and heat treatment of wire is visible here, e.g. possible effect of aging of 8.5 mm wire. The hardness distributions on the cross sections of wires after consecutive passes show similar character for all drawing schedules, where the average hardness increases with increasing deformation. The resulting hardness level in final wires is shown in Fig. 8. In general, the hardness distribution along the wire diameter is quite uniform, with the degree of uniformity increasing with decreasing diameter of initial wire. It should be noticed that hardness distributions do not tend to show the characteristic profile, with the clear minimum at the axis and the increase of hardness towards the wire surface. This character of strain hardening was found to occur only slightly in case of the schedules A (Fig. 8a) and B (Fig. 8b). The difference between hardness values at the center and close to wire surface is small probably due to relatively small die angle, which did not generate large redundant strains. Moreover, in case of the schedules A and B a slight drop in hardness can be seen in surface layers, which can result from the effect of friction hindering the material flow.

The other factors influencing the character of strain hardening of a material can contribute to the obtained results, e.g. the development of texture [7,11,14,24,25] or the formation of strain-induced martensitic phase [1-4,7,9,11,14-16,20,21,23]. The metastable austenitic stainless steels are one of the main steel classes utilizing TRIP (transformation-induced plasticity) effect. Admittedly, no investigations of possible strain-induced martensitic transformation (SIMT) were realized in this research, but it was evidenced in earlier work of the author that the martensitic phase is being created during drawing of this particular steel, amounting to approximately 17% volume fraction for 50% area reduction and reaching 40% when drawn with 90% total reduction [7]. The martensitic transformation of the metastable steel grades induces a high strain hardening effect forcing the tensile strength to become very high. This can be observed in Fig. 4, where the area reduction of about 50% results in the tensile strength level reaching 1400-1800 MPa. Since the SIMT is the basis of TRIP effect, it can be assumed that this effect occurred in the realized experiment. However, it has to be taken into account that the kinetics of SIMT is affected by a number of factors such as chemical composition, austenite grain size, stacking fault energy, stress state, deformation temperature, strain and strain rate, with the resulting stability of austenite being a crucial condition [1-4,15,16,20]. The interdependence between these mechanical and structural phenomena and parameters is planned to be further investigated in the continuation of this research work.

5. Conclusions

The realized experimental investigations and the analysis of the results allow to formulate the following conclusions:

- The influence of the history of deformation and heat treatment on the multi-pass AISI 302 steel wire drawing process is evident. The decrease of the initial wire diameter, which means more extensive history of heat treatment and deformation, results in more uniform drawing force variations in time, concerning its general level. However, at the same time, larger fluctuations of drawing force around the average value are observed.
- The changes of strength properties (tensile strength and yield strength) show some quantitative differences (especially yield strength) for different drawing schedules, which manifests itself by different character of variations of plasticity margin, particularly in the schedules B and C.
- The changes of ductility (elongation and reduction of area at fracture) show similar character for all drawing schedules. Some deviation is only observed as more gentle decrease of elongation in case of the schedule A.
- The technological properties of wire, represented by the number of bends till fracture, show similar character of changes for the schedules B and C. Only in the last passes the reverse tendency is observed (increase of the parameter in case of the schedule B and decrease in the schedule C).
- The effect of the history of deformation and heat treatment on hardness distribution on the cross section of wire becomes evident in the difference of hardness of the feedstock material. The hardness distributions observed in final wires are fairly uniform, with the degree of uniformity increasing with decreasing diameter of initial wire. The higher strain inhomogeneity is to be expected in case of the application of larger die angles.

In summary, it is to be concluded that the history of deformation and heat treatment of the investigated AISI 302 steel wire evidently influences the multi-pass drawing process, which is illustrated by the drawing force variations in time. The effect of the history of deformation and heat treatment on the properties of wire becomes evident in the differences of properties of the feedstock material, as well as in quantitative disparities of the changes of mechanical properties during drawing. Further, it also slightly influences the level of strain non-uniformity. Consequently, it should be emphasized that the knowledge of the initial state of a material to be processed, including its thermomechanical history, proves to be valuable from the point of view of material's behaviour when subjected to deformation.

The continuation of this research is planned in order to extend the analysis of mechanical and structural behaviour of AISI 302 steel, but also other austenitic stainless steel grades, subjected to heavy deformation.

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