

Surface Quality and Mechanical Properties in Drawn Stainless Steel Profile Wires Caused by Process Parameters

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Abstract. Thin profile wires made of stainless steels are widely used for production of industrial screens used for filtration and separation processes. Industrial screens made of resistance spot welded thin profile wires are used e.g. in baskets for centrifuges or filtration screens and find a wide range of applications in various branches of the industry (mining, food and sugar industry, paper industry, wastewater treatment, oil and gas and many more). Regardless of the application, increased durability and surface quality of the screens is of paramount importance. Improvement of the longevity of manufactured items, process efficiency and environmental performance can be achieved only when interactions between initial wire rod quality and its susceptibility to metal forming operations are fully understood. Due to the complexity of the manufacturing process of industrial screens (precise and small gaps, narrow ranges of dimensional tolerances), forming of thin, so-called precision profiled wire is difficult. The influence of the charge, i.e. wire rod, parameters of the wire drawing / rolling process play a key role in obtaining semi-finished products characterized by high strength, low surface roughness and a low level of residual stresses. The paper discusses the influence of the initial state of wire rod and deformation parameters on the quality of thin austenitic and lean duplex steel profile wires as well as the possibility of replacing austenitic wires by lean duplex wires and their possible benefits.

Introduction

The wide use of stainless steels results from their attractive combination of mechanical properties and resistance to chemical corrosion. These steels are used in various engineering applications such as high pressure pipes in power engineering, medical equipment, food industry products, automotive industry etc. There are several basic grades of stainless steel: austenitic, ferritic, martensitic and ferritic-austenitic two-phase steels. The differences between the mentioned grades result not only from mechanical or physical properties (ferromagnetics, paramagnetics) but also from technological properties predisposing them to metal forming processes by e.g. deep drawing or wire drawing. Studies published so far have shown that there is a clear relationship between the type of stainless steel, the microstructure and the mechanical properties. For example, it was shown in [1] that the mechanical properties (hardness and tensile strength) of the duplex stainless steel were about 1.5 times higher than those of the austenitic and ferritic stainless steels. Two main reasons for the high strength of duplex stainless steel were identified as follows: (i) severe interruption of slip deformation in the γ phase on the α phase; (ii) a high misorientation angle around phase boundaries between the γ and α phases, caused by bonding of the different lattice structures: γ -fcc and α -bcc. It has also been observed that the ultimate tensile strength of duplex stainless steel increased with increasing proportion of the γ phase to 50 pct, but decreased with a further increase in the amount of γ phase. Such differentiation of the properties of stainless steels means that the selection of process parameters in the production of profiled wires must be particularly carefully carried out.

One of the important features of stainless steel products is also the high quality of the surface of the products made of them, which has the ability to persist for a long period of operation. Due to these

features, stainless steels are widely used in the production of such products as various types of screens used in the chemical, construction and food industries. The basic structural element of such screens are profiled drawn wires of various sizes and shapes.

The surface flaw of a drawn wire also has a significant influence on the quality of product [2]. There are various types of flaws on the wire surface, such as transversal cracks, scales, scratches, and overfilling of flaws [3]. Most of the defects in drawn wire come from both the initial defects [4, 5] from the preform and the deformation process itself. E.g. even when a scratch on the wire surface appears to be removed after repeated drawing, in reality, the flaw remains inside the wire because of the development of an overlap, and thus it is difficult to completely remove the flaw [6,7]. Profile wires are usually produced by two basic metal forming processes, i.e. wire drawing and wire rolling [8]. In wire rolling, the work rolls are driven whereas in wire drawing dies assembled of non-driven rolls may also be used [9]. In the latter case roller dies are supported by bearings and rotate freely as the wire is drawn through, leading to a rolling friction instead of the sliding friction which occurs when using conventional monolithic dies. In the publication [10] authors described this drawing method and compared it to the conventional drawing method. They observed that for each reduction stage a higher reduction could be selected when using roller dies. They also performed micro hardness measurements on the cross-section of wires reduced using both techniques, stating that hardness was more uniform in the case of wires drawn using roller dies, while conventionally drawn wires were harder at the surface.

This work compares two multi-stage cold forming processes, namely wire drawing and wire rolling, in terms of mechanical properties, microstructure development and surface quality of two grades of stainless steel, i.e. austenitic and two-phase ferritic-austenitic steel. The conducted research also took into account the influence of the development of work hardening of the tested steels, represented by YS / UTS ratio and drawing speed.

Experimental Procedure

In the present study two different materials have been investigated. For the investigation 1.4307 austenite stainless steel and 1.4162 lean duplex stainless steels have been chosen. The difference of materials both in mechanical behaviour as well as the microstructural behaviour are crucial in the development of forming process of thin profile wires. The chemical compositions of used stainless steels are presented in Table 1.

Table 1. Chemical composition of used material [wt. %]

Material	C	Mn	Si	S	P	Cr	Ni	N	Cu	Mo
1.4307	0.02	1.54	0.37	0.006	0.035	18.16	8.10	0.075	-	-
1.4162	0.02	4.77	0.72	0.002	0.037	21.37	1.43	0.22	0.3	0.15

In order to define the relationship between mechanical state and microstructure, the in-situ plastometric tests in an scanning electron microscope chamber were performed. Micromechanical tests were carried out using a in-Situ SEM tensile stage produced by Kammrath&Weiss with a 5 kN load cell. During the measurements, the tensile stage was placed in the chamber of an FEI Versa 3D FEG scanning electron microscope equipped with the EBSD data acquisition system. The system allowed to analyse microstructure and texture changes of the specimens during the plastic deformation tests. The test setup is presented in Fig. 1 a-c,. Flat tensile specimens of a specially designed shape were cut out from initial wire rods (cut in longitudinal direction from the centre of the rods) with EDM according to Fig. 1d.

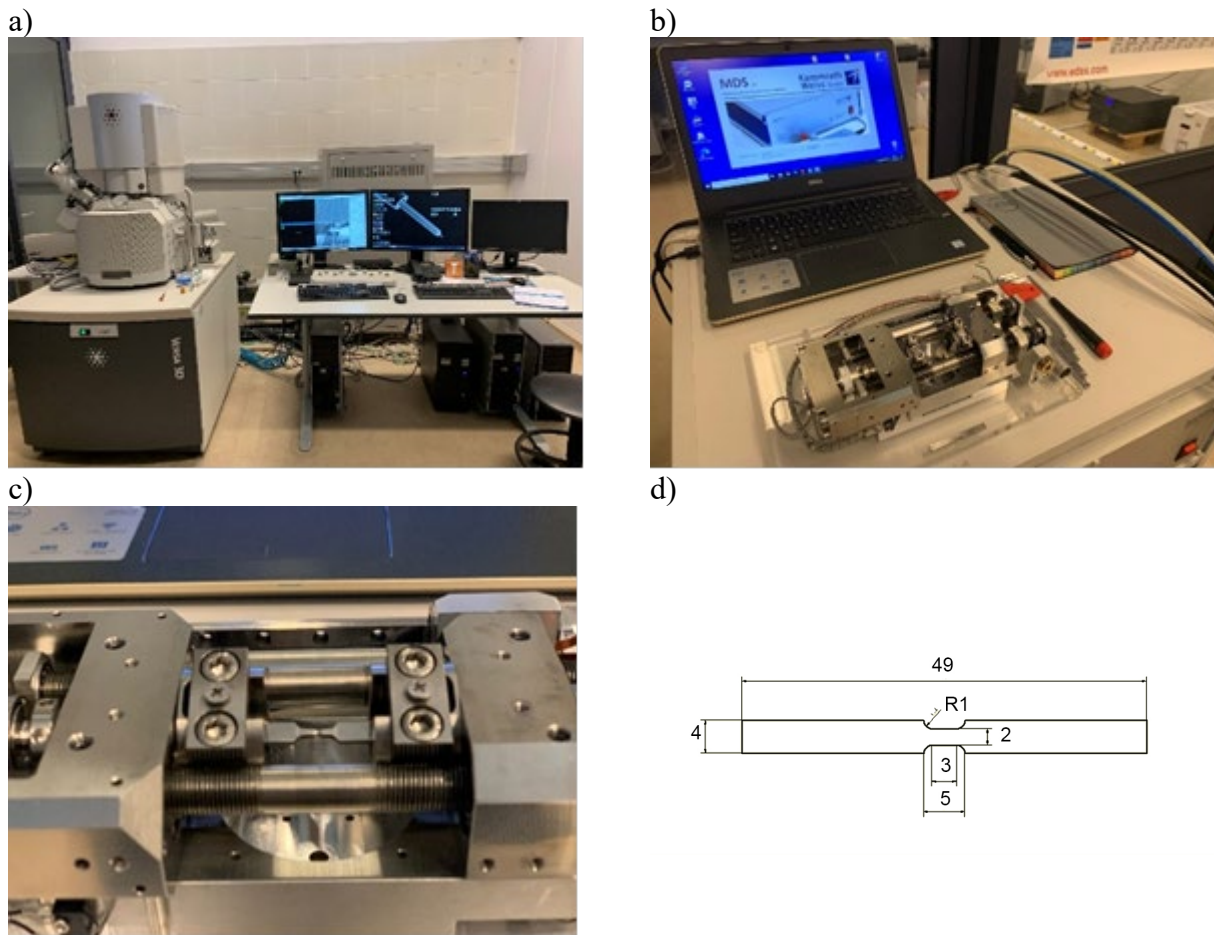


Fig. 1. The in-situ SEM tensile testing setup. SEM FEI Versa -a) tensile test frame -b,c) Shape of used specimen -d). Tensile specimen thickness – 1.5 mm.

A series of EBSD measurements were made for each initial material to illustrate changes in microstructure during plastic deformation. For each sample, EBSD maps were taken at four measurement points: before deformation, after 10% of deformation, after deformation corresponding to half the range of uniform elongation, and at the end of this range. The measurement area of the EBSD maps and the resolution (map measurement step length) were selected for each material separately in order to obtain appropriate grain statistics for each of the image microstructures. Deformation of the specimens in the strain gauge table was carried out at a rate of $12 \mu\text{m/s}$, which corresponds to an initial strain rate of $4 \times 10^{-3} \text{ s}^{-1}$.

In order to analyse the influence of the wire drawing processes on the mechanical properties as well as the surface quality three experimental procedures have been carried out. Two of them were performed under the industrial conditions and third one under laboratory conditions. The schematic presentation of the tests have been presented in Fig 2.

First test was focused on the influence of the deformation method i.e. wire drawing and rolling processes, on the mechanical behaviour resulted in changes of the mechanical properties as well as the surface quality. For the analysis the austenitic stainless steels (1.4307) was selected with the wire diameter of 3.43 mm in the case of rolling and 3.55 mm in the case of drawing. After both deformation methods 28sb profile wire was obtained. The rolling process was conducted in four steps – rolling in the duo rolling machine at the 1st step and then 3 profile rolling mills were used. The drawing process was performed in three steps – 1st deformation step was carried out through 2 rolls while 2nd and 3rd step was conducted using profile roller dies. The specimens after both rolling and drawing process were tested for mechanical properties in the tensile test and the roughness of surface was measured.

Second set of tests was focused on the influence of deformation speed on the mechanical behaviour of lean duplex stainless steel (1.4162). For the test, 5 different drawing speeds were chosen i.e. 40 m/min , 90 m/min , 140 m/min , 200 m/min , 250 m/min. The drawing speed influence was

analysed in the case of 6sb profile that was achieved by drawing from $\phi 1,60$ mm wire. For each specimen after deformation the tensile test as well as the roughness examination have been performed.

Third set of tests was focused on the analysis of the influence of the material structure on the final properties and surface quality. Austenitic stainless steel (1.4307) and lean duplex stainless steel (1.4162) were deformed in the laboratory tests. The wires of $\phi 5.20$ mm for 1.4307 and $\phi 5.15$ mm for 1.4162 were deformed in the same way in order to obtain equal dimensions, i.e. 2×6.57 mm. For each specimen after deformation the tensile test as well as the roughness examination has been performed.

In order to study the rheological properties of the materials the tensile tests at room temperature under quasi-static conditions using ZWICK Z250 machine were conducted. During the test, force versus extension data were recorded and then recalculated into stress – strain curves using standard equations.

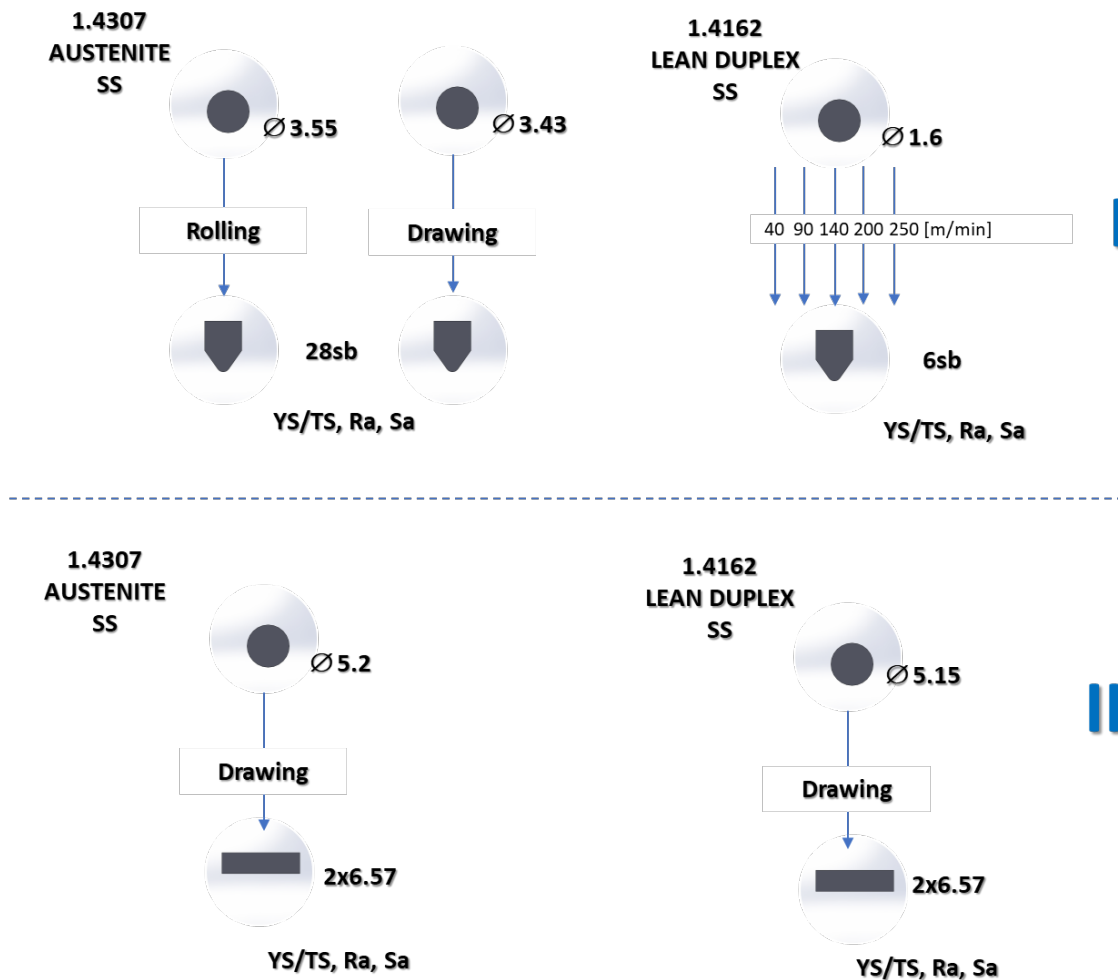


Fig 2. Schematic representation of the conducted tests.

Testing of the topography of the working surfaces of the profiles was carried out using optical profilometer VykoNT9800/9300 from Veeco. On the surface of each profile roughness parameters were measured in 3 to 5 randomly selected places. In all these areas, the surface topography was visualised in two- and three-dimensional images. Linear profiles of surface roughness were also made in places with the greatest surface irregularities (scratches, pitting, etc.).

Table 2. Types of analysis conducted in the research with material and tests characterization.

Lp	Type of analysis	Material	Tests
1	Influence of MF process	1.4307	Tensile test Roughness
2	Influence of drawing speed	1.4162	Tensile test Roughness
3	Influence of material structure	1.4307 1.4162	Tensile test Roughness

Results and Discussion

Structural changes

The analysis of the metal forming process of austenitic and lean duplex thin profile wires was conducted in order to assess the mechanical behaviour of materials and the resulting final mechanical properties and surface quality. In order to obtain the structural changes of stainless steels under deformation process the tensile tests using in-situ SEM tensile stage with EBSD analysis have been conducted. Fig. 3 shows examples of EBSD analysis of 1.4307 austenitic stainless steel at initial state and after different deformation level. The initial microstructure of the 1.4307 consists of mostly equiaxial austenite grains. The average grain size resulting from the EBSD is 13.8 μm , however, it is underestimated due to the presence of smaller grains with irregular, deformed boundaries. These smaller, irregular grains were indexed in EBSD as having a BCC structure in contrast to the FCC of austenite. As a result of plastic deformation, the amount of the BCC phase increased at each measurement point, suggesting that the observed BCC phase is a strain-induced martensitic phase. As a result of the deformation of the material, the proportion of the martensitic phase increases from 21.1% for non-deformed to 50.5% for 30% deformation (Table 3). The formation of martensite structure in the characteristic bands visible on the phase map after 30% deformation suggests that during deformation of the specimen, strain localization occurs even though the microstructure observations do not indicate the formation of macroscopic shear bands.

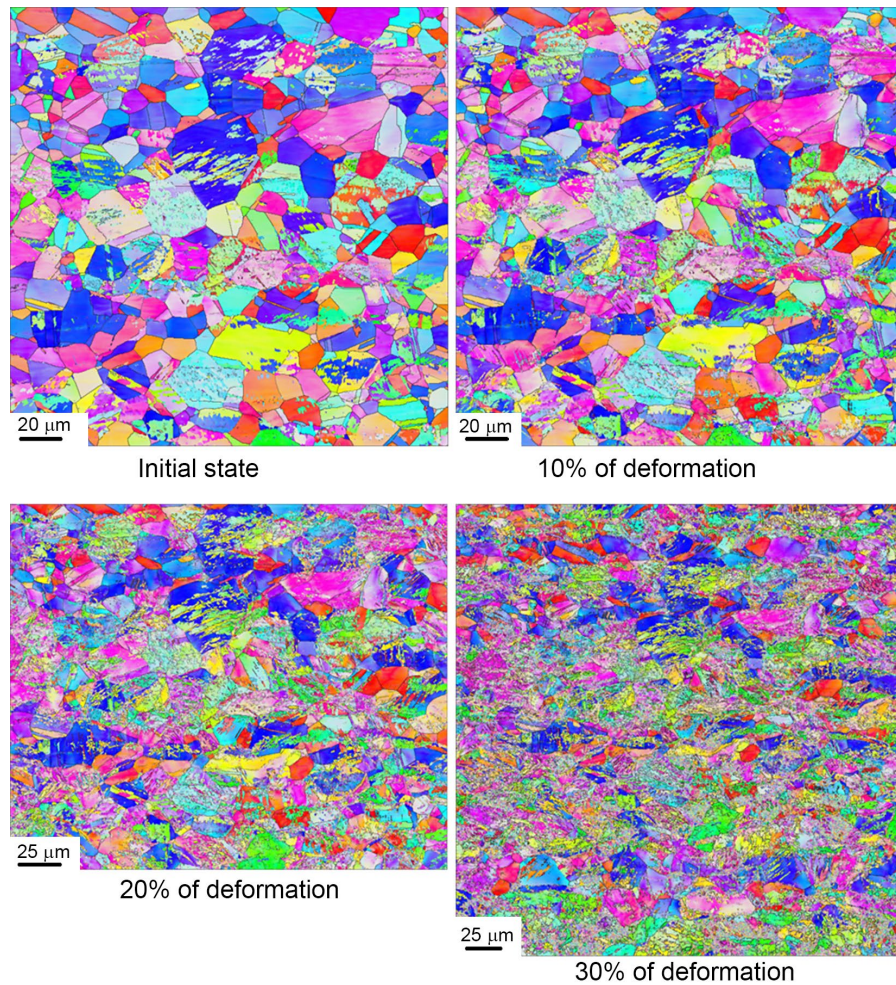


Fig. 3. Microstructure of the 1.4307 austenitic stainless steel at initial stage and after 3 steps of deformation.

On the working surface of the deformed specimen of 1.4307, it can be observed that dislocation slip and twinning boundaries occurs, as well as additional contrast from the revealing boundaries between the austenite lattice and the emerging martensite needles. The apparent phase boundaries result from the geometrical incompatibility of the dislocation deformation occurring in the original austenite grains with the structure of the martensite needles.

Table 3. Volume fraction of Austenite and Martensite Phase in 1.4307 Austenitic Stainless Steel.

Volume fraction, %	Deformation			
	0%	10%	20%	30%
Austenite	78.9	71.7	40.8	49.5
Martensite	21.1	28.3	40.8	50.5

EBSD results of the tensile test of 1.4162 lean duplex steel have been presented in the Fig. 4. Material has a band structure with a bimodal grain size distribution with an average grain size of 7.35 μm . The austenite bands consist of larger, elongated grains without a developed subgrain structure. The ferrite strands, on the other hand, often consist of single, highly elongated grains with an extensive sub-grain structure including a low angle grain boundaries. The initial microstructure of austenite grains contains a number of twin boundaries, but they do not grow during deformation. Few of the deformation twins needles appeared in single grains after deformation up to 20%. Most of the deformation is accomplished by dislocation slip. The increase in dislocation density is mainly observed near the grain boundaries, leading to deterioration of the quality of diffraction images in these areas and some errors in indexing at these points on the EBSD maps. The initial microstructure

consists of 62.3% austenite and 37.7% ferrite. During the deformation, a higher dislocation density is stored in the austenite grains, leading to a deterioration in EBSD indexing quality in these areas what resulted that in the case of 30% strain the amount of grains indexed as austenite is 48.3%. Therefore, the EBSD method is not adequate to assess the austenite content in an quantitative manner in duplex steel.

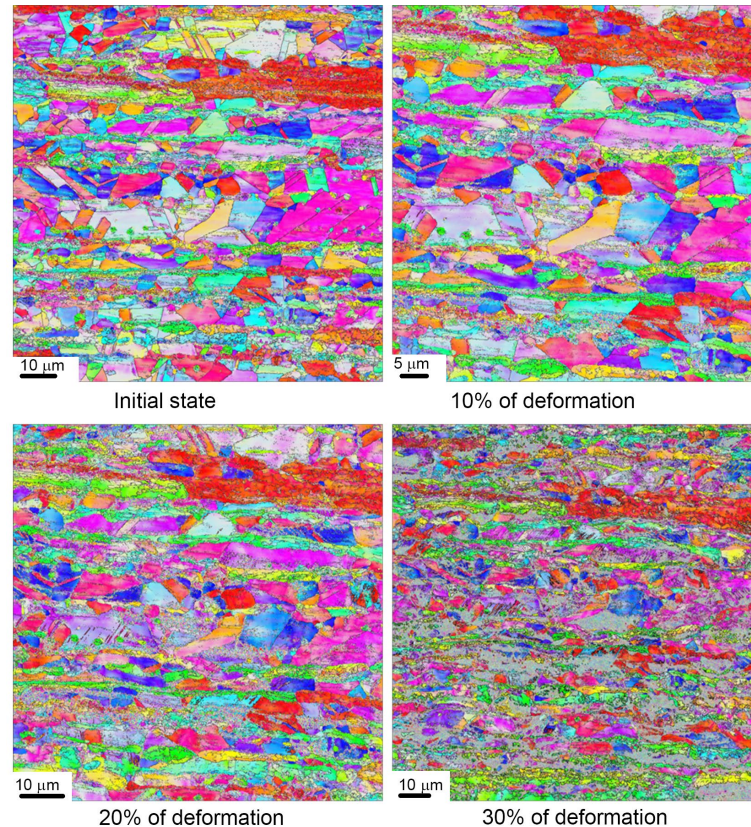


Fig 4. Microstructure of the 1.4162 lean duplex stainless steel at initial stage and after 3 steps of deformation.

The surface of the 1.4162 specimen before deformation has a slight topography originating from the banded microstructure of austenite grains separated by ferrite bands. After exceeding the YS value at strain of 10%, slip traces are observed mainly in austenite grains. Differences in the nature of plastic deformation between austenite and ferrite grains lead to a strong indication of the banded microstructure of the material in further deformation steps.

Influence of Metal Forming Process

The results of mechanical properties of mechanical properties of profile wires obtained using rolling and drawing process are presented in Fig 5. The 28sb profile wire was rolled from the initial diameter of 3,55 mm while the wire drawing process was conducted using initial wire diameter of 3,43mm. In the analysis 1.4307 austenitic stainless steel has been used. The differences in diameters were caused by the industrial process conditions, where different wire diameters have been used in rolling and drawing process. The final mechanical properties of products were measured in order to obtain the YS/TS ratio as it is required for further bending during welding of rounded screens. In both cases an increase of the mechanical properties was observed. Obtained results show that in the case of rolling process YS/TS ratio was equal to 91% while in the drawing was 96% These results clearly show that after rolling process the further steps of the manufacturing process (resistant spot welding and bending) of cylindrical screens will be possible without damages.

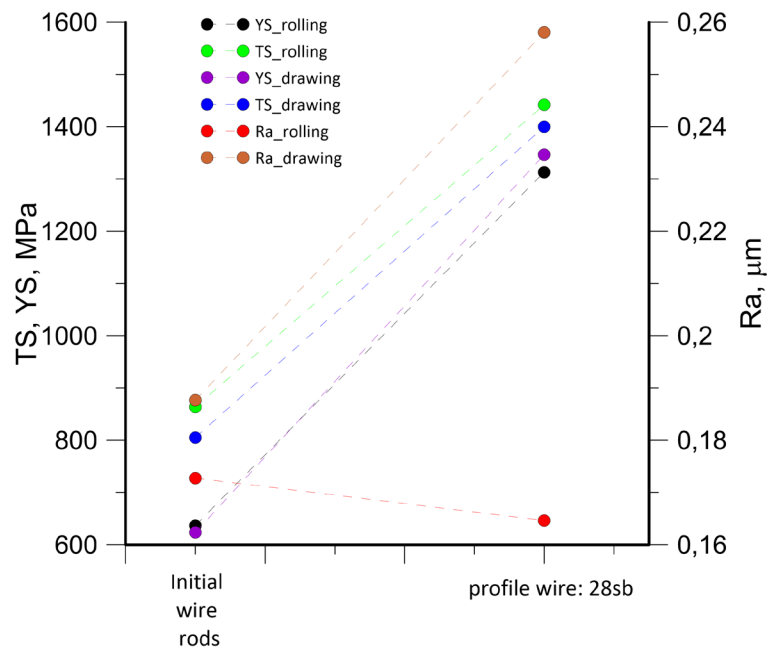


Fig 5. Mechanical properties of the 1.4307 stainless steel after rolling and drawing process

In the industrial screens, the final applications impose very high requirements regarding the roughness of the surface. It is especially required in the screens used in the offshore application like oil mining industry. The initial roughness of the wire intended for rolling process was equal to 0,17 μm and wire for drawing process was equal to 0,18 μm . After rolling Ra decrease to about 0,16 μm while after drawing process Ra increased to 0,25 μm . Such high increase was caused most likely by the low quality of die surface and the stress state obtained in the drawing process. Such observation suggest that for the profile 28sb rolling process is more appropriate.

Table 4. Surface roughness of the profile wires manufactured with different metal forming process

Deformation Method	Profile	Ra _{avg} , μm	Ra standard deviation	Sa _{avg} , μm	Sa standard deviation
Rolling	$\phi 3.43 \text{ mm}$	0.17276	0.02741	0.33105	0.05342
	28sb	0.16464	0.01013	0.51546	0.04887
Drawing	$\phi 3.55 \text{ mm}$	0.18767	0.03662	0.34829	0.03342
	28sb	0.25807	0.02303	0.78199	0.11400

Due to the fact that under industrial conditions it is important to obtain material in the most financial effective way, the second set of tests was focused on the effects of drawing speed. In the analysis 1.4162 lean duplex stainless steel has been used. The results of mechanical properties of profile wires have been presented in Table 6. The influence of drawing speed was analysed in the drawing process of the production of 6sb profile wire where the initial diameter of the wire was 1,6mm.

Influence of Drawing Speed

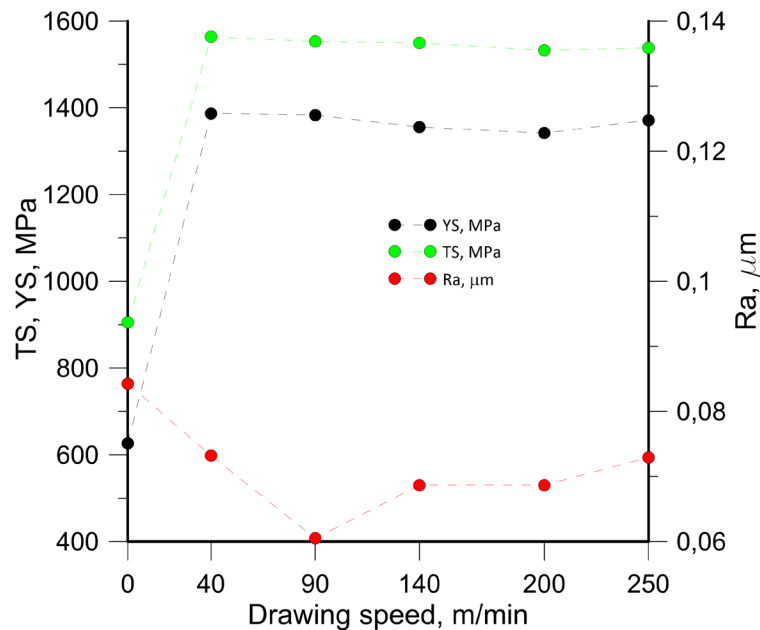


Fig. 6. Mechanical properties of the 1.4162 lean duplex steel after drawing process with various drawing speed

The effect of drawing speed on the mechanical properties of drawn wires has been analysed at the beginning. Increasing the drawing speed decreased both YS and TS. The YS/TS ratio in the case of profile wires subjected for further bending and spot-resistant welding is crucial for proper deformation. When analyzing the speed effect, it can be seen that 140 mm/min has the lowest YS / TS ratio, which may give the best results in the subsequent bending processes.

Table 5. Surface roughness of the profile wires drawn with different drawing speed.

Drawing speed, mm/min	Ra _{avg} , μm	Ra standard deviation	Sa _{avg} , μm	Sa standard deviation
φ1.6mm	0.08426	0.02578	0.14568	0.03881
40	0.07321	0.01726	0.13979	0.00588
90	0.06049	0.00396	0.1306	0.01067
140	0.06867	0.00578	0.13645	0.01343
200	0.06868	0.00277	0.1537	0.02303
250	0.07293	0.01089	0.16745	0.01368

Analysis of the effect of drawing speed on surface quality showed the dependence of the Ra parameter on the speed used. The results have been presented in Table 5. Tests were carried out for 5 different drawing speeds and showed that for the 1.4162 lean duplex, a linear drawing speed of V=90 m/min gave the best results in terms of lowering the roughness parameter Ra from 0.084 to 0.060 μm. Drawing at extreme speeds of V=40 and 250 m/min only slightly reduced the roughness parameter Ra to approx. 0.073 μm. The linear speeds V=140 and 200 m/min had similar roughness values Ra of 0.0686 μm. An important factor controlling surface quality in this case is the quality of lubrication applied for a given drawing speed. It should also be expected that the method of deformation, i.e. rolling or drawing by roll drawing dies, will have an impact on the surface quality of the products due to the different types of friction occurring in both processes. Therefore, when selecting lubricants, it is necessary to take into account the manner in which the deformation takes

place (drawing with rollers or rolling). If we take into account both roughness and mechanical properties, it is suggested that the most effective drawing speed will be when drawing at 140m/min.

Influence of Material Grade

The last analysis was focused on the influence of the equivalent plastic strain on the mechanical properties and surface quality in the 1.4307 austenitic stainless steel and 1.4162 lean duplex stainless steel. The analysis was performed in the laboratory condition where initial diameter of wire was 5,2mm in the case of 1.4307 and 5.15 mm in the case of 1.4162. Final dimension of obtained profile wire was equal to 2,0x6,57.

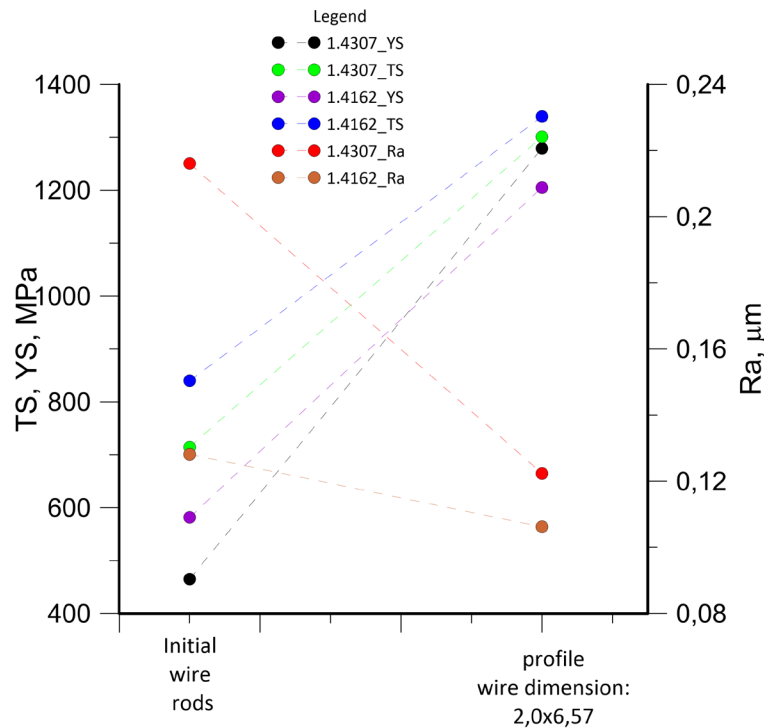


Fig 7. Mechanical properties of the 1.4307 stainless steel and 1.4162 lean duplex stainless steel after drawing process with various equivalent plastic strain

After drawing process mechanical tests were performed both on the initial wire rods and drawn profile wires. The results are presented in Fig 7. The deformation process in both case caused increase in the TS/YS ratio. The difference in final ratio in both materials is equal to 10% and is much lower in the case of 1.4162 lean duplex stainless steel. The further bending will be much more effective in the 1.4162 material because the YS/TS ratio is lower than 90%.

The final surface roughness of materials is on the acceptable level equal to 0,12 μm for 1.4307 and 0,10 μm for 1.4162 steel grade. It has to be stated that the lowering of roughness level is much higher in the case of austenitic stainless steel.

Table 7. Surface roughness of the profile wires drawn with different equivalent plastic strain.

Material	Wire dimension, mm	Equivalent plastic strain	Ra _{avg} , μm	Ra standard deviation	Sa _{avg} , μm	Sa standard deviation
1.4307	$\Phi 5.2$		0.21606	0.04813	0.40681	0.09054
	2.0x6.57	0.47	0.12235	0.03358	0.22525	0.11312
1.4162	$\Phi 5.15$		0.12814	0.02018	0.29915	0.11440
	2.0x6.57	0.46	0.10618	0.00854	0.35275	0.01889

The influence of plastic deformation on two different materials was assessed in order to check whether the austenitic stainless steel can be replaced with duplex stainless steel. Considering both the surface quality and the mechanical properties, the influence of the degree of deformation is more pronounced for 1.4162 lean duplex steel.

Summary

The mechanical and microstructural inhomogeneities of both austenite and austenite-ferrite steels are most often treated as an unexpected effect of the manufacturing process. The combination of regions characterized by the different features contribute to the final properties of the product i.e the mechanical properties as well as the surface quality. In the presented study, it has been shown that by appropriate modification of the parameters of the wire drawing and rolling processes, it is possible to obtain, under industrial conditions, profiles with roughness below $R_a=0.1$. This effect can be obtained by replacing austenitic steels (1.4307) with austenitic-ferritic ones (1.4162), or by appropriate modification of the processing schemes (increasing the number of passes, using other tools or rolling/pulling speeds). Attention should be paid to the importance of frictional conditions, which should be selected during deformation process depending of the deformation method used, i.e. wire rolling or drawing. Based on the conducted tests the following conclusions can be drawn:

- Tensile tests of 1.4307 steel confirmed that deformation induced martensitic transformation is an important element of the strengthening process that defines its susceptibility to cold deformation,
- The type of the profiled wire production process, i.e. rolling or drawing, has a very significant influence on the surface quality of the finished products. The wire rolling process allows to obtain a lower, required roughness of the considered 28 sb profile wires.
- The analysis of the two tested materials showed that in the case of 1.4162 lean duplex steel, both in the drawing and rolling of wires, the roughness is reduced, but in the case of austenitic 1.4307 stainless steel, the lowering in surface quality is more significant.
- The tests were conducted to assess the possibility of replacing austenitic stainless steel with lean duplex steel. The obtained results show that in order to successfully achieve the goal of study proper process conditions have to be used.

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References

- [1] M. Okayasu, D. Ishida, Effect of microstructural characteristics on mechanical properties of austenitic, ferritic, and γ - α duplex stainless steels, *Metall Mater Trans A Phys Metall Mater Sci*, 50a, (2019), 1380-1388
- [2] K. Yoshida, Technological trend and problem in wire drawing of various super fine wires, *J. Jpn. Soc. Technol. Plast.* 41–470 (2000) 194–198.
- [3] K. Yoshida, T. Shinohara, Growth and disappearance of flaws on wire surface in wire drawing, *Wire J. Int.* (2004) 52–57.
- [4] F.C. Magalhães, A.E.M. Pertence, H.B. Campos, M.T.P. Aguiar, P.R. Cetlin, Defects in axisymmetrically drawn bars caused by longitudinal superficial imperfections in the initial material, *J. Mater. Process. Technol.* 212 (2012) 237–248
- [5] H. Moo Baek, Y. G. Jin, S. K. Hwang, Yong-Taek Im, Il-Heon Son, Duk-Lak Lee, Numerical study on the evolution of surface defects in wire drawing, *J. Mater. Process. Technol.* 212 (2012) 776–785
- [6] T. Shinohara, K. Yoshida, Deformation analysis of surface flaws in stainless steel wire drawing *J. Mater. Process. Technol.* 162–163 (2005) 579–584

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- [7] B. Avitzur, B., Metal Forming: Processes and Analysis, 2nd ed. McGraw-Hill, Kierger, Huntington, NY, 1968.
 - [8] T. S. Cao, C. Vachey, P. Montmitonnet, P.-O. Bouchard, Comparison of reduction ability between multi-stage cold drawing and rolling of stainless steel wire – Experimental and numerical investigations of damage, J. Mater. Process. Technol. 217 (2015) 30–47
 - [9] K. El Amine, J. Larsson, L. Pejryd, Experimental comparison of roller die and conventional wire drawing, J. Mater. Process. Technol.. 257 (2018) 7–14
 - [10] J.H. Ekkelenkamp, P.B. Khosrovabadi, P.B., Design and manufacture of a "roller die" system for wiredrawing. Wire J. Int. 22, 27–28 30, (1989) 35–40.