UDK 621.778:620.172
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 47(2)245(2013)

TENSILE PROPERTIES OF COLD-DRAWN LOW-CARBON STEEL WIRES UNDER DIFFERENT PROCESS PARAMETERS

NATEZNE LASTNOSTI HLADNO VLEČENE MALOOGLJIČNE JEKLENE ŽICE PRI RAZLIČNIH PARAMETRIH PROCESA

Cem S. Çetinarslan[1], Ali Güzey[2]
[1]Department of Mechanical Engineering, Faculty of Engineering and Architecture, Trakya University, 22180 Edirne, Turkey
[2]Arsay Wire Production Company-Kirklareli, Turkey
cemc@trakya.edu.tr

Prejem rokopisa – received: 2012-10-01; sprejem za objavo – accepted for publication: 2012-10-23

This study demonstrates the influence of drawing-process parameters such as reduction (deformation) ratio and drawing velocity on the tensile properties of various low-carbon cold-malleable steel wires. Standard tensile tests were realized on four types of wires – SAE1006, SAE1008, SAE1015 (Cq15) and SAE10B22 (20MnB4) – at various process parameters. This experimental study shows how two of the main process parameters, the deformation ratio and drawing velocity, clearly influence the tensile properties (yield stress, ultimate tensile strength, and elongation at rupture) of steel-wire materials.

Keywords: wire drawing, tensile properties, deformation (reduction) ratio, drawing velocity

Ta študija prikazuje vpliv procesnih parametrov pri vlečenju, kot sta odvzem (deformacija) in hitrost vlečenja, na natezne lastnosti različnih malooglјičnih mehkih jeklenih žic. Izvršen je bil standardni natezni preizkus na štirih vrstah žice SAE1006, SAE1008, SAE1015 (Cq15) in SAE10B22 (20MnB4) po različnih procesnih parametrih. Ta eksperimentalna študija je pokazala, kako dva glavna procesna parametra, stopnja deformacije in hitrost vlečenja, vplivata na natezne lastnosti (napetost tečenja, natezna trdnost in raztezek pri pretrgu) jeklene žice.

Ključne besede: vlečenje žice, natezne lastnosti, stopnja deformacije (odvzem), hitrost vlečenja

1 INTRODUCTION

Wire drawing is a metal-reducing process, in which a wire rod is pulled or drawn through a single die or a continuous series of dies, thereby reducing its diameter.

Wire drawing is one of the most common plastic-deformation processes. A wire rod is pulled or drawn through a die or a series of dies, causing a reduction of its diameter. In general, drawing is known as a process performed at room temperature. Drawing of low-carbon-content steel wires is generally conducted at room temperature employing a number of passes or reductions through several dies. Sometimes it may be performed at elevated temperatures for large wires to reduce drawing forces.

Generally, steel wire is made of plain-carbon steel grades. The steel-wire materials are semi-products suitable for cold-drawing processes. Although a steel wire can be produced from stainless steel and other alloyed steels, in industry it is mostly produced using plain-carbon steels. The steel containing up to 1 % C is usually used for steel-wire production; however, the largest part of steel-wire production constitutes low-carbon steels with less than 0.1 % C.[1]

Ferrous wires are used as semi products for electrical wiring, ropes (rope wires are usually made of pearlitic steel and have very high tensile properties), cables, structural components, springs, nails, spokes, musical instruments, electrodes, paper clips, etc.[2]

Several studies on wire-drawing processes and some process parameters that affect the wire-drawing process have been performed. Toribio and Ovejero have investigated the effect of cumulative cold drawing on the pearlite interlamellar spacing in eutectoid steel. Interlamellar spacing in fully pearlitic steels decreases progressively during the cold-drawing process and the diminishing rate is not constant throughout the manufacturing route.[3] The effect of degree of deformations, ranging from 5 % to 30 % reductions, on the mechanical properties of cold-drawn, mild-steel rods was experimentally investigated by Alawode and Adeyemi.[4] Languillaume et al. have presented the results of a study concerning the influence of heavy cold drawing and post-deformation annealings on the microstructure of such pearlitic steel wires.[5] On the other hand, Vega et al. have studied the effect of the process variables such as the semi-die angle, the reduction in area and the friction coefficient on the drawing-force value. The results of this study indicate clearly that friction has a significant effect on the drawing force, which becomes lower due to a decrease in the area reduction.[6] The influence of the main process parameters (the wire yield stress – S, the cross-sectional area reduction – Re and the die half angle – α) on the shape quality and area fraction of the round-to-hexagonal composite wire drawing were investigated by Norasethasopon.[7] This study shows that *Re* and *S* strongly influence the shape quality, and *S* slightly influences the change in the area fraction of the core. The change in the area fraction of the core, which equals zero, was obtained with the value of α that increased with the increasing *S*. *Re* and *S* strongly influence the drawing stress. Within this order, *Re* and *S* directly, strongly and inversely influenced the optimal die half angle. The pass schedule of a wire-drawing process designed to prevent a delamination of a high-strength-steel cord wire was studied by Lee et al.[8] From their findings it is clear that the applied drawing process reduced the diameter of the wire from 3.5 mm to 0.95 mm, and that it consisted of nine passes. On the other hand, another model for predicting the fatigue strength of two different eutectoid-steel wires, one of them being zinc coated, used in ropeway applications, has been presented by Beretta and Boniardi.[2] Within this method the fatigue process of wires has been described in terms of propagation of the surface defects caused by cold drawing.

The aim of our research was to investigate the tensile properties of various low-carbon cold-malleable steel wires with respect to drawing velocity and deformation ratio. These parameters also have an influence on the final wire quality, the drawing force, the lubrication in the process, the mechanical properties and the die wear.

2 EXPERIMENTAL PROCEDURE

2.1 Preparation process

Wire-rod (raw) materials were of four different types of low-carbon steel: SAE1006, SAE1008, SAE1015 (Cq15) and SAE10B22 (20MnB4). The steel chemical compositions are given in **Table 1**.[9]

First, the chemical compositions of the steels were measured using a SPECTROLAB M7 spectrometric test device. Then the surface-cleaning process including two stages, the mechanical and chemical cleaning, was performed. The first step, the mechanical surface cleaning, was applied to remove the scale layer from the wires and then the chemical purification was realized. The chemical cleaning consisted of causticization (for 25 min in a $KMnO_5$ + NaOH solution at 70 °C), dipping into an acid bath (for 1 h in a HCl concentrated solution at room temperature), washing and rinsing, passivation with lime and, finally, drying (for 1h at 100 °C).

2.2 Wire-drawing process

After these treatments the drawing process was performed. **Figure 1** shows the outlet of a drawing die with a coil (end product) and a drawing die (matrix) with a soap box. A wire first passes through the soap box and then through the die (matrix). The reduction of the diameter of a metal wire is realized by pulling it through the die (**Figure 2**). The working region of a die is typically and made of W carbide. The die is cooled with a cooling hose (water) as shown in **Figure 1**. A series of dies is used to obtain the required diameter reduction of the wire. **Table 2** shows a series of dies with the reductions of 5.5 to 2.2, to 1.8 and to 2.1 made in 8 or 9 passes, used to obtain the wire diameters of (4.80, 4.00 and 3.01) mm. The reduction ratio (*R*/%) was determined for each diameter decrease as to the equation:

$$R/\% = \frac{D_{\text{inlet}}^2 - D_{\text{outlet}}^2}{D_{\text{inlet}}^2} \times 100 \qquad (1)$$

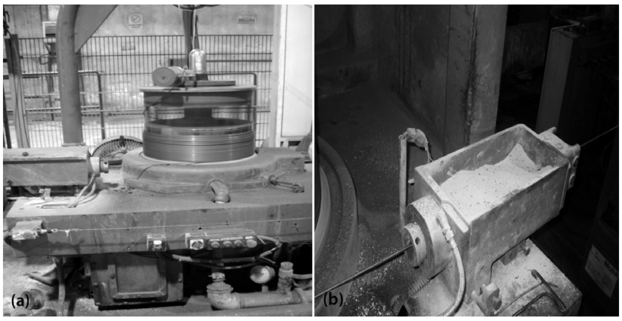

Figure 1: a) Outlets of a drawing die with a wire coil and b) a drawing die (matrix) with a soap box

Slika 1: a) Sestav vlečne matrice z navijalcem žice, b) matrica za vlečenje s posodo za milo

Table 1: Chemical compositions of wire-rod (raw) steels

Tabela 1: Kemijska sestava jekla v palicah

Steel Type	%C	%Si	% Mn	%P	%S	%Cu	%Cr	%Ni	%Mo	%Al	% B
SAE1006	0.06	0.2	0.35	0.04	0.05	0.30	0.15	0.3	0.03	–	–
SAE1008	0.08	0.30	0.55	0.03	0.05	0.35	0.3	0.25	0.03	0,02	–
SAE1015	0.14	0.15	0.40	0.02	0.015	0.1	0.08	0.1	0.05	0.03	
SAE10B22	0.21	0.15	1.00	0.015	0.015	0.1	0.08	0.1	0.05	0.02	0.002

Table 2: Series of dies for each steel type for the drawing process (reduction of 5.5 to 4.8, to 4.00 and to 3.01)

Tabela 2: Serija orodij za vsako vrsto jekla pri vlečenju (odvzem 5,5 do 4,8, do 4,00 in do 3,01)

Inlet dia.	Outlet dia.	Pass number	1	2	3	4	5	6	7	8	9
5.50	2.20	8	4.80	4.21	3.72	3.31	2.96	2.67	2.41	2.20	–
5.50	1.80	8	4.67	4.00	3.44	2.98	2.60	2.29	2.02	1.80	–
5.50	2.10	9	4.82	4.25	3.77	3.37	3.02	2.73	2.49	2.28	2.10

Figure 2: Drawing die (matrix) with a tip (pressure type)
Slika 2: Orodje za vlečenje (matrica) s konico (tlačne vrste)

In a multipass drawing process, the temperature rise during each pass can affect the mechanical properties of the final product (such as its bending and torsion properties, and its tensile strength).[8]

A wire-drawing process was carried out with different drawing velocities and different total-reduction ratios of the deformation to determine how the tensile properties of various low-carbon wires were affected.

The effect of drawing velocity and deformation ratio was investigated in some references. One of those focused on the influence of drawing speed on the properties of multiphase TRIP (transformation induced plasticity) steel wires[10] and the other on the study of the effect of total-reduction ratio on wire breaks by Cu fine-wire drawing.[11]

In general, each pass ratio is between 1.68 and 1.09.

$$D_{\text{final-1}} = k \cdot D_{\text{final}} \qquad (k = 1.68\text{–}1.09) \tag{2}$$

2.3 Tensile test

Experiments were carried out on a tensile-test machine at room temperature (**Figures 3** and **4**) and

Figure 3: Tensile-test machine
Slika 3: Stroj za natezne preizkuse

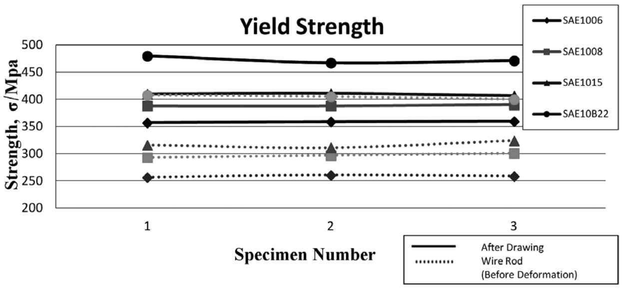

Figure 4: Variation in the yield-strength values for a rod and coil steel wire at a constant velocity and reduction ratio (from ϕ5.50 to ϕ4.81)
Slika 4: Spreminjanje meje plastičnosti palice in žice v kolobarju pri konstantni hitrosti in odvzemu (od ϕ5,50 do ϕ4,81)

SAE1006, SAE1008, SAE1015 (Cq15) and SAE10B22 (20MnB4) coil wires (end products) were used as test steels. The wires were submitted to tensile tests to determine the yield stress, the ultimate tensile strength and the elongation at rupture. Wire cuts of 250 mm in length were used as the test specimens. The tensile strength was determined on a 3 t tensile tester with a ram (lower jaw) speed of 10 mm/min using various test parameters and three experiments were carried out and then averaged for each point in the diagrams.

3 RESULTS AND DISCUSSIONS

3.1 Test results at a constant drawing velocity (3.6 m/s) and a constant reduction ratio (from ϕ5.50 to ϕ4.81)

Firstly, the wire-rod specimens were tested and then the coil (drawn) wires were tested at a constant drawing velocity and a constant reduction ratio from ϕ5.50 to ϕ4.81. Experimental findings on the yield strength, tensile strength and elongation at rupture were determined for wire rods (before drawing) and coil (drawn) wires and are given in **Table 3**.

The yield-strength values of rod wires and coil wires were found as expected and, as shown in **Figure 4**, they increase in accordance with the increasing C content. The increase in the C content causes brittleness, making

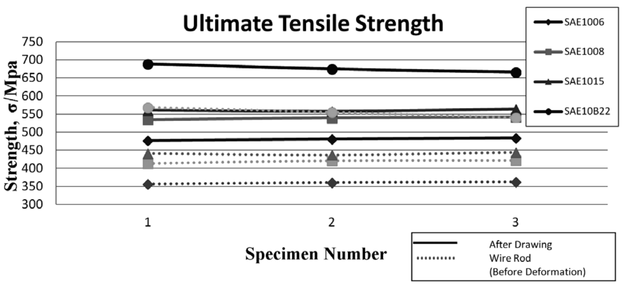

Figure 5: Variation in the ultimate tensile-strength values for a rod and coil steel wire at a constant velocity and reduction ratio (from ϕ5.50 to ϕ4.81)
Slika 5: Spreminjanje vrednosti natezne trdnosti palice in žice v kolobarju pri konstantni hitrosti in odvzemu (od ϕ5,50 do ϕ4,81)

Table 3: Tensile properties of a rod and coil steel wire at a constant drawing velocity and a constant reduction ratio (from ϕ5.50 to ϕ4.81)
Tabela 3: Natezne lastnosti palice in žice v kolobarju pri konstantni hitrosti vlečenja in konstantnem odvzemu (od ϕ5,50 do ϕ4,81)

Specimen No	Dia., ϕ/mm		Material type	V m/s	Yield Strength $Rp_{0,2}$/MPa		Ultimate Tensile Strength R_m/MPa		Elongation at Rupture %	
	Wire rod (before drawing)	Coil (after drawing)			Wire rod (before drawing)	Coil (after drawing)	Wire rod (before drawing)	Coil (after drawing)	Wire rod (before drawing)	Coil (after drawing)
1	ϕ5.50	ϕ4.81	SAE1006	3.6	257	357	357	477	41	29
2	ϕ5.50	ϕ4.81	SAE1006	3.6	261	359	361	481	44	30
3	ϕ5.50	ϕ4.81	SAE1006	3.6	259	360	363	484	43	31
1	ϕ5.50	ϕ4.81	SAE1008	3.6	293	388	413	535	39	32
2	ϕ5.50	ϕ4.81	SAE1008	3.6	297	388	421	540	38	28
3	ϕ5.50	ϕ4.81	SAE1008	3.6	301	390	422	542	40	29
1	ϕ5.50	ϕ4.81	SAE1015	3.6	316	410	441	561	41	28
2	ϕ5.50	ϕ4.81	SAE1015	3.6	311	411	437	558	40	28
3	ϕ5.50	ϕ4.81	SAE1015	3.6	324	407	444	564	41	32
1	ϕ5.50	ϕ4.81	SAE10B22	3.6	408	480	568	689	36	25
2	ϕ5.50	ϕ4.81	SAE10B22	3.6	405	467	555	675	37	26
3	ϕ5.50	ϕ4.81	SAE10B22	3.6	400	471	540	666	39	29

plastic deformation more difficult. The ultimate tensile-strength values of the rod materials and coils of the tested steels are also in line with the increasing C content (**Figure 5**). The variation in the elongation at rupture is shown in **Figure 6**. The values of the elongation at rupture for drawn wires decreased with the increasing plastic deformation for all the tested steels. The (20MnB4) steel shows a slight decrease in the elongation due to a higher C content.

The wire specimens used for the tensile tests are shown in **Figures 7** and **8**.

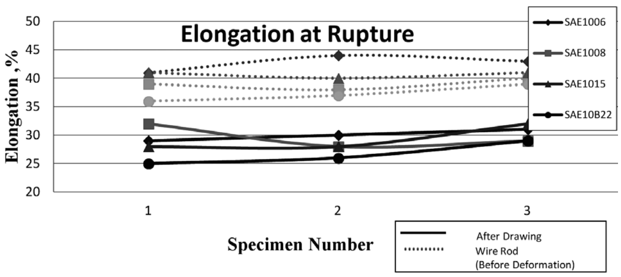

Figure 6: Variation in the elongation-at-rupture (%) values for a rod and coil steel wire at a constant velocity and reduction ratio (from ϕ5.50 to ϕ4.81)
Slika 6: Spreminjanje raztezka pri pretrgu (%) za palico in žice v kolobarju pri konstrantni hitrosti in odvzemu (od ϕ5,50 do ϕ4,81)

3.2 Test results at a constant drawing velocity (3.6 m/s) and different reduction ratios (from ϕ5.50 to ϕ4.81, to ϕ4.00 and to ϕ3.01)

The coil materials were tested at a constant drawing velocity (3.6 m/s) and different reduction ratios (from ϕ5.50 to ϕ4.81, ϕ4.00 and ϕ3.01). The reduction ratio was determined as depending on the constant inlet diameter (ϕ5.50) and different outlet diameters (ϕ4.81, ϕ4.00 and ϕ3.01). Experimental findings are given in **Table 4**. The yield strength, tensile strength and elongation at rupture were determined for the wire rods (before drawing) and for drawn wires after various reduction ratios.

Figure 7: SAE1008 specimen
Slika 7: Vzorec SAE1008

Figure 8: SAE10B22 (20MnB4) specimen
Slika 8: Vzorec SAE10B22 (20MnB4)

Table 4: Tensile properties of a rod and coil steel wire at a constant drawing velocity (3.6 m/s) and different reduction ratios (from ϕ5.50 to ϕ4.81, to ϕ4.00 and to ϕ3.01)

Tabela 4: Natezne lastnosti palice in žice v kolobarju pri konstantni hitrosti vlečenja (3,6 m/s) in različnih odvzemih (od ϕ5,50 do ϕ4,81, do ϕ4,00 in do ϕ3,01)

Specimen No	Dia., ϕ/mm		Material type	V m/s	Yield Strength $Rp_{0,2}$/MPa		Tensile Strength R_m/MPa		Elongation at Rupture %	
	Wire rod (before drawing)	Coil (after drawing)			Wire rod (before drawing)	Coil (after drawing)	Wire rod (before drawing)	Coil (after drawing)	Wire rod (before drawing)	Coil (after drawing
1	ϕ5.50	ϕ4.81	SAE1006	3.6	258	357	359	477	43	36
2	ϕ5.50	ϕ4.00	SAE1006	3.6		505		605		24
3	ϕ5.50	ϕ3.01	SAE1006	3,6		623		725		12
1	ϕ5.50	ϕ4.81	SAE1008	3.6	294	388	407	535	42	34
2	ϕ5.50	ϕ4.00	SAE1008	3.6		536		643		22
3	ϕ5.50	ϕ3.01	SAE1008	3.6		664		774		11
1	ϕ5.50	ϕ4.81	SAE1015	3.6	316	410	438	561	40	33
2	ϕ5.50	ϕ4.00	SAE1015	3.6		558		676		18
3	ϕ5.50	ϕ3.01	SAE1015	3.6		684		808		8
1	ϕ5.50	ϕ4.81	SAE10B22	3.6	406	480	571	689	38	31
2	ϕ5.50	ϕ4.00	SAE10B22	3.6		649		811		15
3	ϕ5.50	ϕ3.01	SAE10B22	3.6		772		944		5

The yield-strength values for all the specimens increase with the increasing reduction ratio (**Figure 9**); and the ultimate tensile strength for all the specimens shows similar tendencies (**Figure 10**). Variations in the elongation at rupture are shown in **Figure 11**. In general, the values of the elongation at rupture for coil wires decrease as the reduction ratio increases. The decrement is a bit larger for the relatively high C-content steel specimens, SAE1015 (Cq15) and SAE10B22 (20MnB4), as the increase in the reduction ratio is more effective for the steels containing a higher C content with respect to the strain hardening. In addition, the Mn content is also a strength-increasing alloying element for the steel SAE10B22.[12]

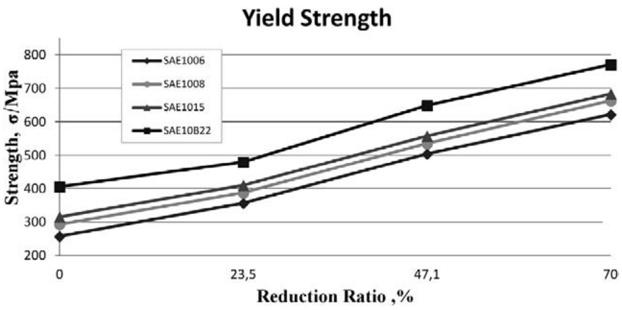

Figure 9: Variation in the yield-strength values for a rod and coil steel wire at a constant velocity and different reduction ratios (from ϕ5.50 to ϕ4.81, to ϕ4.00 and to ϕ3.01)

Slika 9: Spreminjanje meje plastičnosti za palico in žico v kolobarju pri konstantni hitrosti in različnih odvzemih (od ϕ5,50 do ϕ4,81, do ϕ4,00 in do ϕ3,01)

3.3 Tensile-test results at a constant drawing velocity (3.6 m/s) and different reduction ratios – different inlet diameters and constant outlet diameters

Firstly, the wire rods were tested. The tests for coil wires were realized at the constant drawing velocity (3.6 m/s) and different reduction ratios (from ϕ5.50 to ϕ4.81

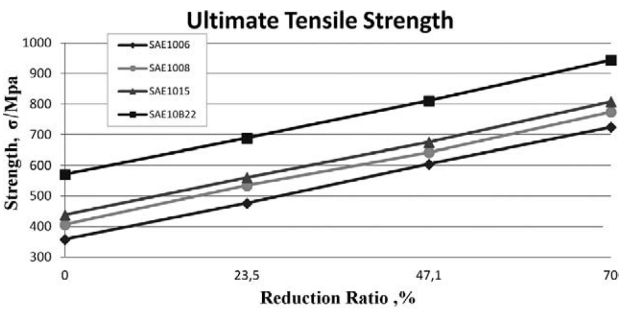

Figure 10: Variation in the ultimate-tensile-strength values for a rod and coil steel wire at a constant velocity and different reduction ratios (from ϕ5.50 to ϕ4.81, to ϕ4.00 and to ϕ3.01)

Slika 10: Spreminjanje naztezne trdnosti palice in žice v kolobarju pri konstantni hitrosti in različnih odvzemih (od ϕ5,50 do ϕ4,81, do ϕ4,00 in do ϕ3,01)

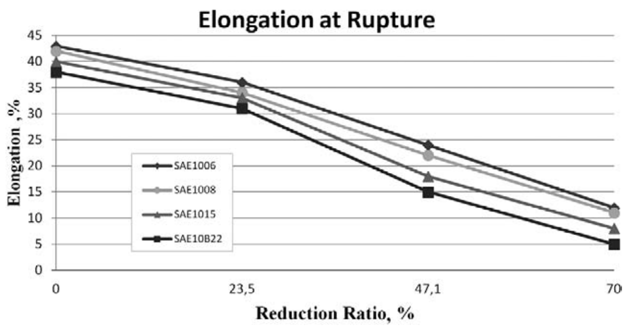

Figure 11: Variation in the elongation-at-rupture (%) values for a rod and coil steel wire at a constant velocity and different reduction ratios (from ϕ5.50 to ϕ4.81, ϕ4.00 and to ϕ3.01)

Slika 11: Spreminjanje raztezka pri pretrgu (%) palice in žice v kolobarju pri konstantni hitrosti in različnih odvzemih (od ϕ5,50 do ϕ4,81, do ϕ4,00 in do ϕ3,01)

Table 5: Tensile properties of a rod and coil steel wire at a constant velocity (3.6 m/s) and different reduction ratios – different inlet diameters and a constant outlet diameter – (from ϕ5.50 to ϕ4.81 and from ϕ6.50 to ϕ4.81)

Tabela 5: Natezne lastnosti palic in žice v kolobarju pri konstantni hitrosti (3,6 m/s) in različnih odvzemih – različen vstopni premer in enak izhodni premer – (od ϕ5,50 do ϕ4,81 in od ϕ6,50 to ϕ4,81)

Specimen No	Dia., ϕ/mm		Material type	V m/s	Yield Strength $Rp_{0,2}$/MPa		Tensile Strength R_m/MPa		Elongation at Rupture %	
	Wire rod (before drawing)	Coil (after drawing)			Wire rod (before drawing)	Coil (after drawing)	Wire rod (before drawing)	Coil (after drawing)	Wire rod (before drawing)	Coil (after drawing)
1	ϕ5.50	ϕ4.81	SAE1006	3.6	258	357	358	477	43	36
2	ϕ6.50	ϕ4.81	SAE1006	3.6		500		605		24
1	ϕ5.50	ϕ4.81	SAE1008	3.6	292	388	405	535	42	34
2	ϕ6.50	ϕ4.81	SAE1008	3.6		531		643		22
1	ϕ5.50	ϕ4.81	SAE1015	3.6	314	410	436	562	40	33
2	ϕ6.50	ϕ4.81	SAE1015	3.6		553		676		18
1	ϕ5.50	ϕ4.81	SAE10B22	3.6	406	480	567	689	38	31
2	ϕ6.50	ϕ4.81	SAE10B22	3.6		645		811		15

and from ϕ6.50 to ϕ4.81). These ratios were determined according to different inlet diameters and constant outlet diameters. The results are shown in **Table 5** and **Figures 12**, **13** and **14**. The yield strength, tensile strength and elongation at rupture were determined for the wire rods

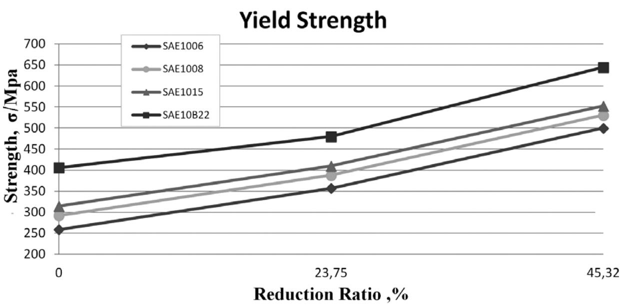

Figure 12: Variation in the yield-strength values for a rod and coil steel wire at a constant velocity (3.6 m/s) and different reduction ratios – different inlet diameters and constant outlet diameters (from ϕ5.50 to ϕ4.81 and from ϕ6.50 to ϕ4.81)

Slika 12: Spreminjanje meje plastičnosti palice in žice v kolobarju pri konstantni hitrosti (3,6 m/s) in različnih odvzemih – različen vstopni premer in enak izstopni premer (od ϕ5,50 do ϕ4,81 in od ϕ6,50 do ϕ4,81)

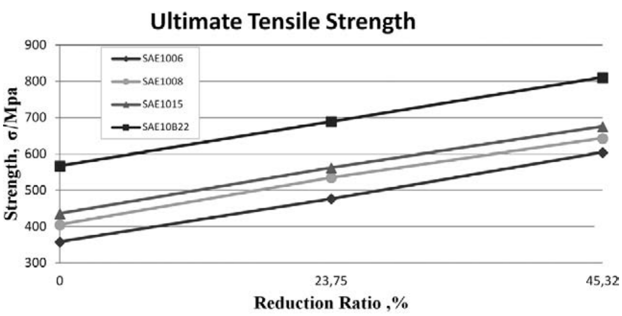

Figure 13: Variation in the ultimate-strength values for a rod and coil steel wire at a constant velocity (3.6 m/s) and different reduction ratios – different inlet diameters and constant outlet diameters (from ϕ5.50 to ϕ4.81 and from ϕ6.50 to ϕ4.81)

Slika 13: Spreminjanje natezne trdnosti palice in žice v kolobarju pri konstantni hitrosti (3,6 m/s) in različnih odvzemih – različen vstopni premer in konstanten izstopni premer (od ϕ5,50 do ϕ4,81 in od ϕ6,50 do ϕ4,81)

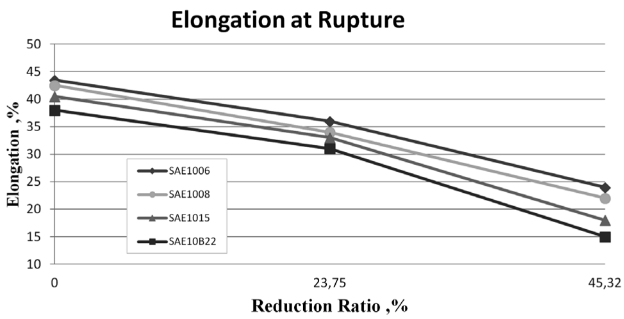

Figure 14: Variation in the elongation-at-rupture (%) values for a rod and coil steel wire at a constant velocity (3,6 m/s) and different reduction ratios – different inlet diameters and constant outlet diameters (from ϕ5.50 to ϕ4.81 and from ϕ6.50 to ϕ4.81)

Slika 14: Spreminjanje raztezka pri pretrgu (%) palice in žice v kolobarju pri konstantni hitrosti (3,6 m/s) in različnih odvzemih (od ϕ5,50 do ϕ4,81 in od ϕ6,50 do ϕ4,81)

(before drawing) and coil (drawn) wires with different ratios.

The yield strength, ultimate tensile strength and elongation at rupture were affected by the reduction ratio for each material as shown in Section 3.2. As the approximate reduction ratios (45.7 % for the reduction of ϕ6.5 to ϕ4.81 and 47.1 % for the reduction of ϕ5.50 to ϕ4.00) were considered, it was understood that the variation in the inlet diameters was not significant.

3.4 Tensile-test results at a constant reduction ratio (from ϕ5.50 to ϕ4.81) and with different drawing velocities (3.6 m/s and 2.4 m/s)

The coil-wire tests were realized at a constant reduction ratio from ϕ5.50 to ϕ4.81 and different drawing velocities (3.6 m/s and 2.4 m/s). The results are shown in **Table 6** and **Figures 15**, **16** and **17**. It is observed that the yield stress and the ultimate tensile strength of the specimens increase with the increasing drawing velocity for each type of the materials. A higher C content leads to a higher yield and ultimate tensile

Table 6: Tensile properties of a coil steel wire at a constant reduction ratio and different drawing velocities (3.6 m/s and 2.4 m/s)
Tabela 6: Natezne lastnosti žice iz kolobarja pri konstantnem odvzemu in različnih hitrostih vlečenja (3,6 m/s in 2,4 m/s)

	Dia., ϕ/mm		Material type	V m/s	Yield Strength $Rp_{0,2}$/MPa	Tensile Strength R_m/MPa	Elongation at Rupture, %
Specimen No	Wire rod (before drawing)	Coil (after drawing)			Coil (after drawing)	Coil (after drawing)	Coil (after drawing)
1	ϕ5.50	ϕ4.81	SAE1006	3.6	357	477	36
2	ϕ5.50	ϕ4.81	SAE1006	2.4	310	455	38
1	ϕ5.50	ϕ4.81	SAE1008	3.6	388	535	34
2	ϕ5.50	ϕ4.81	SAE1008	2.4	350	510	36
1	ϕ5.50	ϕ4.81	SAE1015	3.6	410	561	33
2	ϕ5.50	ϕ4.81	SAE1015	2.4	370	536	35
1	ϕ5.50	ϕ4.81	SAE10B22	3.6	480	689	31
2	ϕ5.50	ϕ4.81	SAE10B22	2.4	444	650	33

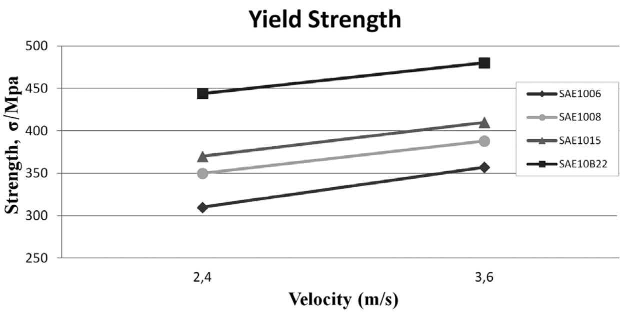

Figure 15: Variation in the yield-strength values for a coil steel wire at a constant reduction ratio (from ϕ5.50 to ϕ4.81) and with different drawing velocities (3.6 m/s and 2.4 m/s)
Slika 15: Spreminjanje meje plastičnosti žice v kolobarju pri konstantnem odvzemu (od ϕ5,50 do ϕ4,81) in različnih hitrostih vlečenja (3,6 m/s in 2,4 m/s)

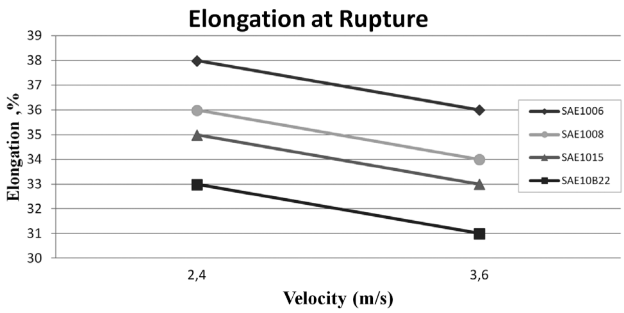

Figure 17: Variation in the elongation-at-rupture (%) values for a coil steel wire at a constant reduction ratio (from ϕ5.50 to ϕ4.81) and with different drawing velocities (3.6 m/s and 2.4 m/s)
Slika 17: Spreminjanje raztezka pri pretrgu (%) žice iz kolobarja pri konstantnem odvzemu (od ϕ5,50 do ϕ4,81) in različnih hitrostih vlečenja (3,6 m/s in 2,4 m/s)

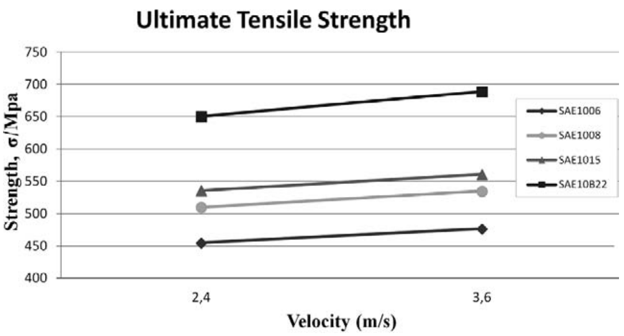

Figure 16: Variation in the ultimate-tensile-strength values for a coil steel wire at a constant reduction ratio (from ϕ5.50 to ϕ4.81) and with different drawing velocities (3.6 m/s and 2.4 m/s)
Slika 16: Spreminjanje natezne trdnosti žice iz kolobarja pri konstantnem odvzemu (od ϕ5,50 do ϕ4,81) in različnih hitrostih vlečenja (3,6 m/s in 2,4 m/s)

strength and a higher drawing velocity. Drawing velocity slightly affects the elongation, which decreases as the drawing velocity increases. These values are quite similar for all the steels.

4 CONCLUSIONS

The wire drawing of SAE1006, SAE1008, SAE1015 (Cq15) and SAE10B22 (20MnB4) low-carbon, malleable-steel wires was investigated and their tensile properties were determined experimentally. This study contributes to the knowledge of tensile properties and the behaviour of drawn low-carbon steel wires during the cold-drawing process. The effect of the process parameters (reduction ratio, drawing velocity) were studied and it was found that the processing parameters have a major influence on the tensile properties in all four types of the low-carbon drawn steel wire.

The obtained results can be summarized as follows:

- The experiments have shown that the yield strength and ultimate tensile strength increase, while the elongation at rupture decreases for all the steels when the reduction (deformation) ratio is increased.
- The drawing velocity has a significant effect on the tensile properties (the yield and the ultimate tensile strength) of low-carbon steel wires. A high drawing velocity causes high strength properties. The values of elongation at rupture also decrease as the drawing velocity increases.

- It was determined that the reduction ratio has a larger influence on the tensile properties of low-carbon steel wires than the drawing velocity.
- Due to a high C content, the tensile-strength properties of the wires increased for all the reduction ratios. In addition, Mn was also one of the strongly influential elements and its effect was amplified by increasing the strain rate for the SAE10B22 steel.[12,13] The increase in the C content enhances the work-hardening rate.[14] The work-hardening ability of steel increases with an increase in the C content. Thus, the C content causes a significant variation in the tensile strength of drawn steel wires. Moreover, it is known that B enhances the tensile properties of low-carbon steels.[15,16]
- The strength of rod wires can be improved using the wire-drawing process according to the experimental findings in this investigation. Furthermore, the wire-drawing-process parameters, like the reduction ratio and drawing velocity, also have a significant effect on the tensile properties of steel wires.

Acknowledgements

The authors would like to thank Mr. Uğur UZ for his help with the experimental work and to the ARSAY WIRE PRODUCTION COMPANY, Kirklareli/Turkey and the YILMAR STEEL WIRE AND SPRING COMPANY, Bursa/Turkey for their technical support in the experimental processes.

5 REFERENCES

[1] T. Altan, S. Oh, H. L. Gegel, Metal forming, ASM, New York, 1983

[2] S. Beretta, M. Boniardi, Fatigue strength and surface quality of eutectoid steel wires, Int. J. Fatigue, 21 (**1999**), 329–335

[3] J. Toribio, E. Ovejero, Effect of cumulative cold drawing on the pearlite interlamellar spacing in eutectoid, Scripta Mater, 39 (**1998**) 3, 323–328

[4] A. J. Alawode, M. B. Adeyemi, Effects of degrees of deformation and stress-relief temperatures on the mechanical properties and residual stresses of cold drawn mild steel rods, J. Mater. Process. Tech., 160 (**2005**) 2, 112–118

[5] J. Languillaume, G. Kapelski, B. Baudelet, Evolution of the tensile strength in heavily cold drawn and annealed pearlitic steel wires, Mater. Lett., 33 (**1997**), 241–245

[6] G. Vega, A. Haddi, A. Imad, An investigation of process parameters effect on the copper-wire drawing, Mater. Design, 30 (**2009**), 3308–3312

[7] S. Norasethasopon, Influence of process parameters on shape quality and area fraction in round-to-hexagonal composite wire drawing, J. Mater. Process. Tech., 203 (**2008**), 137–146

[8] S. K. Lee, D. C. Ko, B. M. Kim, Pass schedule of wire drawing process to prevent delamination for high strength steel cord wire, Mater. Design, 30 (**2009**), 2919–2927

[9] A. Güzey, The Investigation of manufacturing process of ferrous wires, MSc Thesis, Trakya University, Natural and Applied Science Institute, Edirne 2009

[10] M. Suliga, Z. Muskalski, S. Wiewiórowska, The influence of drawing speed on properties of TRIP steel wires, J. Achieve. Mater. Manuf. Eng., 26 (**2008**) 2, 151–154

[11] H. Cho, H. H. Jo, S. G. Lee, B. M. Kim, Y. J. Kim, Effect of reduction ratio, inclusion size and distance between inclusions on wire breaks in Cu fine wiredrawing, J. Mater. Process Tech., 130–131 (**2002**), 416–420

[12] A. A. Gol'denberg, N. P. Sukhikh, T. M. Mineeva, Effect of manganese and nickel on the strength of steel under rigid loading conditions, Met. Sci. Heat Treat., 13 (**1971**) 6, 487–489

[13] M. Itabashi, K. Kawata, Carbon content effect on high-strain-rate tensile properties for carbon steels, Int. J. Impact Eng., 24 (**2000**), 117–131

[14] R. Song, D. Ponge, D. Raabe, Improvement of the work hardening rate of ultrafine grained steels through second phase particles, Scripta Mater., 52 (**2005**), 1075–1080

[15] M. I. Haq, N. Ikram, The effect of boron addition on the tensile properties of control-rolled and normalized C-Mn steels, J. Mater. Sci., 28 (**1993**) 22, 5981-5985

[16] P. Haušild, J. Siegl, P. Málek, V. Šíma, Effect of C, Ti, Zr and B alloying on fracture mechanisms in hot-rolled Fe–40 (at.%)Al, Intermetallics, 17 (**2009**), 680–687