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RESIDUAL STRESS IN MICROALLOYED STEEL SHEET

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The hot rolling sheet production technology leaves behind in the sheet residual surface stress fields, which are due to the uneven strip cooling during rolling, the process of coiling, coil cooling and cold deformation during uncoiling. What concerns cold deformation during coil straightening, we expect that after exceeding the yield point in a surface layer on the tensile strained side, compressive residual stress remains there, and on the other, compressed side tensile residual stress. The influence of surface residual stress on properties of hot rolled steel KODUR E460 TS, KODUR E550 TS and KODUR E700 TS is investigated in this work.

Key words: *hot rolled sheets, residual stress, residual stress monitoring*

Zaostala naprezanja u mikrolegiranom čeličnom limu. Proizvodnom tehnologijom toplo valjanog lima nastaju zaostala naprezanja u površinskim područjima lima i to zbog neravnomjernog hlađenja trake tijekom valjanja, procesa namotavanja trake, hlađenja namota trake te hladnog deformiranja tijekom odmotavanja trake. Što se tiče hladnog deformiranja tijekom ravnanja namota, očekuje se da će se nakon granice razvlačenja u površinskom sloju na strani istezanja pojaviti zaostalo naprezanje nastalo sabijanjem, a na drugoj, komprimiranoj strani zaostalo vlačno naprezanje. U ovom radu je istraživan utjecaj zaostalog površinskog naprezanja na svojstva vruće valjanog čelika KODUR E460 TS, KODUR E550 TS i KODUR E700 TS.

Ključne riječi: *toplo valjani limovi, zaostalo naprezanje, praćenje zaostalog naprezanja*

INTRODUCTION

The residual stresses in metallic parts and structures are a natural consequence of the manufacturing technology e.g. casting, rolling, coldwork, welding and quenching [1]. Residual is the stress in the material without any external mechanical or thermal loading. The residual stress fields are always in equilibrium in a part or structure.

The level of internal residual stresses in hot rolled steel sheet has recently been recognised as an important quality parameter. If it is not known, problems may arise in the following processing operations due to gradients intensity of residual stresses field, for instance the longitudinal cuts are curved, the cut shapes are deformed, the welds are deformed, etc. Even the lowering of corrosion resistance of spiral welded large diameter tubes was ascribed to the influence of residual stresses in the steel sheet [2]. Problematic claims arise because of residual stress in the produced steel sheet. The majority of problems are caused by thermal or strain caused residual stress fields, producing unpredictable changes in shape or dimension, where the internal equilibrium of the field is changed by the cut. The residual stress fields are caused due to the production technology, for instance hot or cold rolling, the coiling, the coil cooling and the cold deformation during uncoiling or flattening.

The thermal residual stress fields are due to uneven strip cooling during the rolling in the output stage when the sides of the sheet are colder than the middle, Figure 1. The stress

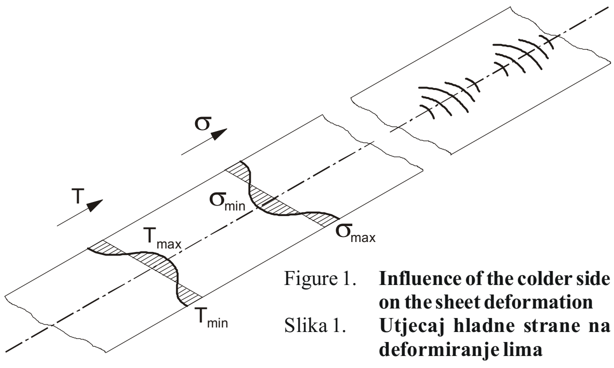

Figure 1. **Influence of the colder side on the sheet deformation**
Slika 1. **Utjecaj hladne strane na deformiranje lima**

caused by the temperature difference ΔT is $\sigma = E_T \alpha_T \Delta T$; where: E_T is the material elastic modulus at the actual tem-

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perature, and α_T is the thermal expansion coefficient at the given temperature.

The sheet is coiled at about 600 °C, when it is strained with plastic deformation. The coil is cooled down and both, relaxation and new residual stress fields arise due to the faster cooling on outer surfaces of the coil. In ref. [3] the thermal residual stresses were assessed after controlled hot rolling and cooling of a 3 m wide sheet, with finishing temperatures from 680 to 780 °C. A maximal residual stress as high as 100 MPa was found.

The residual stress monitoring of the 8 mm thick steel sheet, grade ČSN 11378 [2] revealed in different locations along the rolling direction stress levels from +100 to -100 MPa. The next stage causing residual stress is the uncoiling. On one side residual tensile stresses are formed in and on the other compression stresses as shown in Figure 2. The stresses and their depth of penetration depend on the coiling radius. Generally, a very complicated residual stress pattern is built up in all directions, influenced by the accumulated history of thermal and mechanical loads. The straightening of misshapen longitudinal cutouts, curved because of residual stresses [4], is labour consuming and also the mechanical properties can be influenced. References show too, that the fatigue crack growth is influenced by residual stress caused by coldwork [5, 6] and the fatigue crack can be diverted by residual stress [7, 8]. Though, the following processing of the sheet is influenced very much with residual stress fields in the steel sheet, the problem was not investigated accordingly.

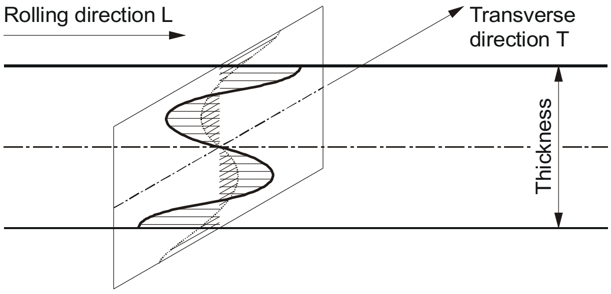

Figure 2. **Residual stress distribution across the thickness in rolling direction *L* and transverse direction *T***
Slika 2. **Raspored zaostalog naprezanja po dubini materijala u pravcu valjanja *L* i poprečno na smjer valjanja *T***

Table 1. **Chemical composition of tested steel**
Tablica 1. **Kemijski sastav ispitivanog čelika**

Material	Element content [%]						
KODUR	C	Mn	Si	P	S	Al	Mo
E700 TS	0.11	1.81	0.04	0.012	0.005	0.092	0.363
E550 TS	0.08	1.52	0.01	0.010	0.006	0.051	
E460 TS	0.08	1.26	0.02	0.017	0.006	0.049	
KODUR	V	Nb	Cu	Ni	Cr	Ti	N
E700 TS	0.003	0.061	0.015	0.014	0.015	0.031	0.013
E550 TS	0.082	0.046				0.014	0.008
E460 TS		0.045				0.024	0.007

EXPERIMENTAL MATERIAL

Microalloyed steel sheets with higher yield strength from 503 to 754 MPa and thickness from 6 to 10 mm were tested. The chemical composition of the tested steel is in Table 1. and the mechanical properties of sheets are in Table 2.

Table 2. **Mechanical properties of tested steel plates**
Tablica 2. **Mehanička svojstva ispitivanih čeličnih ploča**

Location in coil	Sheet thickness and width [mm]	Grade KODUR	R_e [MPa]	R_m [MPa]	A_5 [%]
Head, body, tail	10; 1055	E700 TS	754	835	12.6
Head, tail	8; 1260	E550 TS	568	635	25.8
Tail	6; 1260	E460 TS	503	585	26.4

RESIDUAL STRESS MONITORING

From the tested steel sheet KODUR E700 TS specimens were cut out from the head, the middle part and from the tail of the coil. Three specimens of size of 250 x 250 mm were cut out on even location, one from the right side, one from the middle, one from the left side and then used to assess the residual stresses in the coiled sheet.

Residual stress assessment with elastic deformation on cuts

The method is based on the measurement of deviations from linearity or flatness on surfaces after cuts in both directions: longitudinal *L* and transverse *T*. In the tested line a sheet of a width of 20 mm was cut out and the difference from the flatness measured. Residual stresses relaxation in cuts is a visible permanent elastic deformation and can be used for the assessment of the residual stress difference. It is supposed that the residual stresses are uniform along the cut and can be calculated as a uniform load on a bend beam. The stress can be calculated:

$$\sigma_{zv} = \frac{4.8 \cdot f \cdot E \cdot h}{L^2} \text{ [MPa]} \qquad (1)$$

where:

σ_{zv} - is the residual stress [MPa];
f - the deviation from flatness of the cut 20 mm sheet (deflection in the middle) [mm];
E - material elastic modulus [MPa];
h - sheet thickness [mm];
L - specimen length [mm].

Residual stresses assessment with measurements with resistance strain gauges

Measurements were performed using the system RS 200, testing the residual stress relaxation around holes with a diameter of 2 mm bored to the depth of 4.5 mm in increments of 0.5 mm. Multidirectional resistance strain gauges were glued into the center of the tested 250 x 250 mm specimen, and the main stress values σ_{max} and σ_{min} of plain stress were calculated. Specimens cut from the body of the coil on upper and lower sides and specimens cut from the head and tail of the coil on the lower side only were tested.

For steel sheet of grades KODUR E550 TS and KODUR E460 TS the tests were carried out by assessment of deformations on cuts of width of 20 mm prepared from specimens 250 x 250 mm.

RESULTS AND DISCUSSION

Residual stresses evaluation by elastic deformation on cuts 20 mm wide

The permanent elastic deformation in the middle of the cutout was + 0.368 mm, for the steel KODUR E700 TS and for the specimen cut from the middle of the sheet and the middle of the body of the coil. The residual stress was calculated using the formula (1) and the value of σ_z = + 64.4 MPa obtained, indicating the sign a tensile stress on the upper surface of the sheet. The same calculations for other locations produced the residual stress values shown in Table 3.

Table 3. **Residual stress values for tested steel sheets**
Tablica 3. **Vrijednosti zaostalog naprezanja za čelične limove**

Material	Location in the coil	Direction	Residual stress [MPa] 125 mm from left side	middle of sheet	125 mm from right side
KODUR E700 TS	Coil head (Z)	*L*	-	+2.3	
		T	-		-10
	Body of coil (S)	*L*	+47	+64	
		T	-20		-24
	Tail (K)	*L*	-	+4	
		T	-		-6.8
KODUR E550 TS (z1)	Coil head (Z)	*L*	+5	+9.4	
		T	+10		-24
	Body of coil (S)	*L*	-3.6	+115	
		T	+8		+13
KODUR E550 TS (z2)	Body of coil (S)	*L*	+27	+94	
		T	-4.9		-8.3
KODUR E460 TS	Tail (K)	*L*	-35	+6.7	
		T	-4.3		+2.3

As the results show, the largest residual stress calculated for the steel KODUR E700 TS was in the direction of rolling in the middle of the sheet in the body of the coil and amounted to 64 MPa, and the lowest residual stress of 2.3 MPa was determined in the middle of the head of the coil. There is plain stress in the sheet with these dimensions, on the upper surface tensile stress and on the lower compression usually. Any cutting changes the equilibrium. As result, the ends of the 20 mm cutout are bent up. The absolute value of the tensile stress on the upper surface of the body is usually larger than the compression stress on the lower surface. On both sides of the sheet tested 125 mm from the rim, the residual stress is lower than in the middle. The specimens of this steel grade showed in majority compression stress on the upper side and in transverse direction.

The results determined for steel grades KODUR E550 TS and KODUR E460 TS were similar. The largest residual stress values were determined in the body of the coil in the middle of the sheet in the rolling direction *L* (+ 115 and + 94 MPa). The residual stress values are higher than for the steel KODUR E700 TS and due to the larger width of the sheet and the higher difference in temperatures at the cooling, both during rolling and in the coil. The sides of the sheet showed different stress levels and signs (bending directions) in both tested directions *L* and *T*.

Residual stresses assessment with resistance strain gauges

The residual stress for the steel sheet KODUR E700 TS in the middle of the body of the coil are in Figure 3. A tensile stress on the upper surface was confirmed, though the σ_{max}. stress value in longitudinal direction is significantly

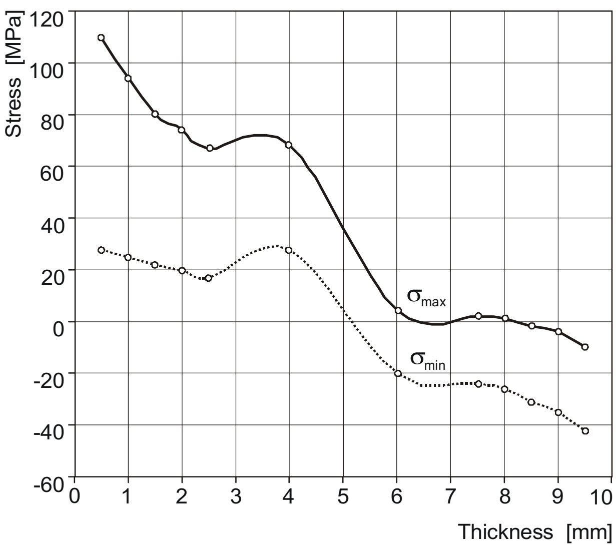

Figure 3. **Residual stress distribution across the thickness of the steel sheet KODUR E700**
Slika 3. **Raspored zaostalog naprezanja po luku čeličnog lima KODUR E700**

higher than the transverse stress value σ_{min}. The values on the surface are the highest and they gradually decrease with the increasing depth. The deviation of the main stress σ_{max} axis on the upper surface from the rolling direction was small - 4, that on the lower surface of the sheet was + 10. The integrated action of the stress field relaxation across the sheet thickness causes a deflection of the 20 mm cutout. Measurements on other specimens showed the compression on the lower surface of the sheet, too. The residual stress values measured in the surface of the tested sheet KODUR E700TS 0.5 mm deep are in Table 4.

Table 4. **Residual stress values in the steel sheet surface 0.5 mm deep in KODUR E700TS**
Tablica 4. **Vrijednosti zaostalog naprezanja na površini če1ičnog lima debljine 0.5 mm u KODUR E700TS**

Location in coil	Surface	Stress [MPa] σ_{max}	σ_{min}	Axis deviation β [°]
Head	Lower	- 8	- 22	- 86
Body	Upper	+ 110	+ 28	- 4
	Lower	- 10	- 42	81
Tail	Lower	- 7	- 15	90

The deviation of the main stress σ_{max} axis on the surface from the rolling direction is labeled with β. The obtained results were similar to the former ones. The largest residual stress values were measured in the body of the coil in the middle of the sheet.

CONCLUSION

The residual stress determination on micro alloyed steel sheets with yield strength from 503 to 754 MPa and thickness from 6 to 10 mm showed the presence of residual stress fields in the tested sheets. It has been confirmed that the stress relaxation after cuts can cause the deformation of cutouts. The largest residual stress was found in the direction of rolling in the middle of the sheet and in the body of the coil and it is tensile stress (+) on the upper surface. The stress levels obtained were from 64 to 115 MPa. The residual stress in the head and tail of the coil is lower also for the middle of the sheet. On both sides of the sheet the residual stress is lower than in the middle. The sides of the sheet showed different stress levels and signs in both tested directions *L* and *T*. The majority of specimens showed compression (-) on the upper side in the transverse direction. The obtained results are in good agreement with ref. [2] and [3]. The residual stresses did form during the elaboration due to cooling differences in the coils. The stress distribution is influenced with the processing after coiling. The cold work during uncoiling influences the residual stress pattern significantly by the differences in layers coldworked at bending. Uncoiling produces residual stress; tension is in the upper surface and compression in the lower surface, as shown in Figure 2. The uncoiling residual stress should be uniform over the sheet. The real residual stresses patterns are influenced with the thermal history of the sheet during coil cooling. The lack of symmetry in the stress distribution can lead to deformation after cutting, as shown in Figure 3.

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