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DEVELOPMENT OF HOT ROLLED COILS IN S355J2+N GRADE WITH Si CONTENT ≤0.03% IN ŽELEZARA SMEDEREVO HOT STRIP MILL

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Abstract

Because of suitability for hot-dip zinc-coating, there is some concern about the use low silicon (Si) content in normalized or normalizing rolling S355J2+N structural steel with minimum specified yield strength of 355 MPa. However, decreasing Si content leads to a decrease of solid solution hardening, whereas decrease in strength should be compensated by alternative mechanism. One possible solution is the use of microalloying with niobium (Nb). Based on available results obtained on own and competitive material, we projected and produced S355J2+N hot-rolled coils (HRC). The results show that the produced material fully satisfies the requirements of the EN 10025-2/2004 quality standard. Furthermore, strength values in normalized conditions were lower than those in normalizing rolling condition.
Key words: normalizing rolling, microalloying, Nb , hot-rolled coils

Introduction

Some of hot rolled steel grade are delivered in normalized or normalizing rolling conditions. The ideal normalizing rolling process is characterized by full recrystallization between hot rolling passes and a finishing temperature that is equal to the austenitizing temperature originally used in the heat treating furnace.

The final aim was to obtain a ferrite-pearlite microstructure with fine and homogeneous grain size.

According to EN 10025-2/2004 standard, normalizing rolling is a process in which the final deformation is carried out in a certain temperature range leading to a material condition equivalent to that obtained after normalizing, so that the specified values of the mechanical properties are retained even after normalizing. The abbreviated form of this delivery condition is +N [1].

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However, normalized rolled material must show limited alterations of its mechanical properties after an additional normalizing heat treatment i.e. a maximum loss of 50 to 60 MPa in yield strength [2].

A particular challenge is to guarantee the value of specified tensile properties of high strength steels, such as S355J2+N grade.

In this sense, one possible solution is to apply microalloying with Nb [3, 4]. However, due to its effect on retardation of recrystallization, addition of Nb carries certain risks, such as a decrease of material strength during normalizing treatment and occurrence of partial recrystallization of austenite, which significantly affects microstructural homogeneity, with a potential negative impact on the plate toughness.

The object of this paper is development of hot rolled coils of S355J2+N grade with low Si content, taking into account the results obtained during production of similar grade with higher Si content on produced in Železara Smederevo hot strip mill, and those obtained on sample of competitive material produced at Tata Steel Ijmuiden Hot Strip Mill-Netherlands (HSM).

Materials and experimental procedure

During ordering material, customer **Benteler** specified hot-rolled coils of S355J2+N grade according to EN 10025-2/2004 as shown in Table 1.

Table 1. Specified parameters

Parameter	Value
Nom.Thickness [mm]	6.00
Nom.Width [mm]	2000
Content of **Si** [mas.%]	Max.0.03
Quantity [t]	100

From material and process point of view, there are two important issues of specified values:

a. Content of Si in steel, decreases potential for solid solution hardening, consequently leading to the achievement of higher level of strength;
b. Finish rolling of S355J2+N grade steel strip in size of 6.00×2000 mm is critical from the overloading point of view of the first finishing stands.

Results and discussion

Available results obtained during production of S355J2+N grade in Železara Smederevo d.o.o HSM correspond to the material with Si=0.15-0.25%. Since the specified materials should contain Si content below 0.03%, this lack of solid solution strengthening due to Si, should be compensated by other alternative mechanism.

It is suggested that this mechanism should grain size refining and precipitation strengthening, due to addition of Nb.

In order to select the appropriate steel composition and process parameters of hot rolling, we carried out an analysis of the available results obtained on the internal NM05 and NM06 steel grade.

The data obtained for NM05 and NM06 hot rolled coils are shown in Tables 2 and 3, respectively.

Table 2. Data of NM05 hot rolled coils (HRC)

NM05	$H_{tr.}$	**C**	**Mn**	**Si**	**Nb**	
min	5,50	0,145	0,750	0,155	0,016	
avg	6,96	0,160	0,870	0,195	0,019	
max	10,00	0,175	0,950	0,245	0,020	
NM05	R_{e+N}	R_{e+NR}	$\Delta R_{e\ NR-N}$	R_{m+N}	R_{m+NR}	$\Delta R_{m\ NR-N}$
min	300	370	70	440	500	60
avg	370	447	77	473	542	68
max	440	510	70	510	580	70

Table 3. Data of NM06 hot rolled coils (HRC)

NM06	$H_{tr.}$	**C**	**Mn**	**Si**	**Nb**	
min	12,50	0,142	1,342	0,160	0,037	
avg	14,04	0,155	1,417	0,187	0,041	
max	15,00	0,191	1,495	0,212	0,047	
NM06	R_{e+N}	R_{e+NR}	$\Delta R_{e\ NR-N}$	R_{m+N}	R_{m+NR}	$\Delta R_{m\ NR-N}$
min	390	460	70	500	560	60
avg	415	502	87	526	597	72
max	440	550	110	550	630	80

The mechanical properties shall comply with the values given in Table 4.

Table 4. Tensile properties and impact strength for S355J2+N grade, accrording to EN 10025-2/2004

Parameter	**Min**	**Max**
R_{e+N} [MPa]	355	
R_m [MPa]	470	630
A [%]	20	
$KV_{2average}$ [J]	27	
$KV_{2individual}$ [J]	19	
T [°C]	-20	
Delivery condition	+N	

Where:

H_{tr} : Nominal thickness of hot rolled coils;
R_{e+NR} : Yield strength in normalizing rolling condition (+NR);
R_{e+N} : Yield strength in normalized condition (+N);
R_{m+NR} : Tensile strength in normalizing rolling condition (+NR);
R_{m+N} : Tensile strength in normalized condition (+N);
ΔR_{e+NR-N} : Difference between yield strength in normalizing rolling and normalized condition;
ΔR_{m+NR-N} : Difference between tensile strength in normalizing rolling and normalized condition.

The chemical composition and mechanical properties measured in the laboratory of Zelezara Smederevo d.o.o, on a sample of hot-rolled strip of S355J2+N grade, produced at Tata Steel Ijmuiden HSM, are shown in Tables 5 and 6, respectively.

Table 5. Chemical composition of the sample hot-rolled coil produced at Tata Steel Ijmuiden HSM

MILL	$H_{st.}$ [mm]	$B_{st.}$ [mm]	C	Mn	Si	P	S
TATA STEEL	8,00	2000	0,15	1,52	0,021	0,0170	0,0045
	Al	Nb	Ti	V	N	C_{IIW}	
	0,03	0,017	0,003	0,006	0,0058	0,42	

Table 6. Mechanical properties of the sample hot-rolled coil produced at Tata Steel Ijmuiden HSM

MILL	TATA STEEL	
Heat	N4507	N4507
N^oProduct	5354030	5354030
$H_{st.}$ [mm]	8,00	8,00
R_e	439	413
R_m	523	543
A	29,6	23,3
R_e / R_m	0,84	0,76
$KV_{avg.}$	226	123
$KV_{2\,(1)}$	221	127
$KV_{2\,(2)}$	226	117
$KV_{2\,(3)}$	231	124
t ^oC	-20	-20
Condition	N	NR
Grain Size	10	9,5

Figure 1 Shows optical micrographs of tested sample of Tata Steel Ijmuiden HRC.

The microstructure of Fig. 1 is essentially ferrite-pearlite, uniformly distributed across the thickness and with some pearlit banding. Ferrite grain size, determined by method EN ISO 643 2014 is about $N^{\underline{o}}$ 10.

Based on the available results shown in Tables 2 and 3, experience in the production of microalloyed steel [5], as well as results obtained on competitive Tata Steel Ijmuiden material (Tables 5 and 6), we projected the product and process design of S355J2+N hot-rolled coils with 6.00mm nominal thickness .

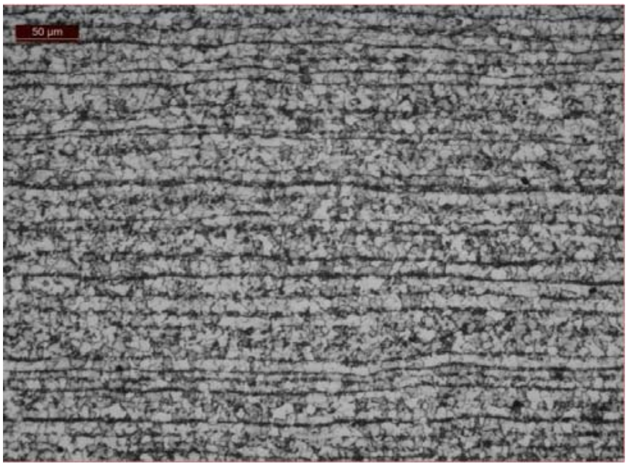

Fig.1. Optical micrograph of sample S355J2+N grade, produced at Tata Steel Ijmuiden HSM with 8.00mm thickness.

The chemical composition and hot rolling process parameters of designed steel are shown in Tables 7 and 8, respectively.

Table 7. Chemical composition of projected steel, designated for S355J2+N grade with 6.00 mm thickness

Grade	C	Mn	Si	P	S	Al	N	B
	0.146	1.295	0.000			0.025		
	0.174	1.505	0.030	0.0150	0.0080	0.050	0.0084	0.0005
NM12*	**Nb**	**Ti**	**V**	**Cu**	**Ni**	**Cr**	**Mo**	**C_{IIW}**
	0.020	0.010						
	0.030	0.015	0.005	0.050	0.050	0.050	0.020	0.45

* ZELEZARA SMEDEREVO d.o.o. steel mark

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

Table 8. Projected parameters of hot rolling process

$T_{sl.\ reh.prg.}$	$t_{sl.reh.prg.}$	$N^{o}_{Pass.prg.}$	$T_{tb.prg.}$
1230	210	7	28
1250			30
$H_{st.prg.}$	$B_{st.prg.}$	$T_{FR.prg.}$	$T_{C.prg.}$
5.81	2000	890	580
6.31	2025	910	630

Where the abbreviation "prg" means programmed value for the following paremeters:

$\mathbf{T}_{sl.reh.prg}$: slab reheating temperature in [^{o}C], $\mathbf{t}_{sl.reh.prg.}$: reheating time in [min], $\mathbf{N}^o{}_{Pass.prg.}$: number of roughing passes, $\mathbf{T}_{tb.prg}$: transfer bar temperature in [^{o}C], $\mathbf{H}_{st.prg.}$: final thickness of HRC in [mm], $\mathbf{B}_{st.prg.}$: final width of HRC in [mm],

$\mathbf{T}_{FR.prg.min.}$: finish rolling temperature in [^{o}C], $\mathbf{T}_{C.prg.min.}$: coiling temperature in [^{o}C].

In order to meet the specified requirements given in Table 1, five slabs from heat number 348846 were cast. Actual (measured) chemical composition of the cast slabs are shown in Table 9.

Table 9. Chemical composition of cast slabs, designated for S355J2+N grade with 6.00 mm thickness

HEAT NUMBER: 348846							
C	**Mn**	**Si**	**P**	**S**	**Al**	**N**	**B**
0,162	1,379	0,025	0,0140	0,0050	0,050	0,0054	0,0001
Nb	**Ti**	**V**	**Cu**	**Ni**	**Cr**	**Mo**	$\mathbf{C}_{IIW}$
0,029	0,013	0,005	0,020	0,020	0,020	0,001	0,400

Comparing results shown in Table 9 with projected ones in Table 7, it may be seen that the actual chemical composition of the heat 348846 fully satisfies the projected values. The cast slabs from a heat 348846, was rolled at HSM according to the rolling schedule 5C53, which was the same as for a hot-rolled coils numbered from 38 to 42, in size of 6.00 x 2000 mm. As for example, the Table 10 shows actual values of parameters of heating, roughing, finishing and coiling processes.

Table 10. Actual parameters of hot rolling process

$\mathbf{T}_{sl.\ reh.prg.}$	$\mathbf{t}_{sl.reh.prg.}$	$\mathbf{N}^o{}_{Pass.prg.}$	$\mathbf{T}_{tb.prg.}$
1250	215	7	29.4
1260	224		30.5
$\mathbf{H}_{st.prg.}$	$\mathbf{B}_{st.prg.}$	$\mathbf{T}_{FR.prg.}$	$\mathbf{T}_{C.prg.}$
6.08	2007	901	610
6.15	2017	903	649

Taking into account the above presented results, as well as impact coefficients of important parameters [5,6], Table 11 shows the expected values of tensile properties in the normalized condition. Table 12 shows the measured values of mechanical properties and ferrite grain size, together with specified values (shaded).

Table 11. Predicted values of tensile properties

Srength	$\mathbf{R}_{e+N}$	$\mathbf{R}_{m+N}$
min.	434	525
max.	501	585

Table 12. Measured and specified values of mechanical properties

Parameter	**Unit**	**Value**				
Heat	[-]	348846				
Slab	[-]	10	20	30	40	50
Schedule	[-]	5D53				
Coil number	[-]	38	39	40	41	42
$\mathbf{R}_{eH\ prg.min.\ +N}$	[MPa]	355	355	355	355	355
$\mathbf{R}_{eH\ act.\ +N}$	[MPa]	464	453	436	471	439
$\mathbf{R}_{eH\ act.\ +NR}$	[MPa]	487	476	485	487	481
$\mathbf{\Delta R}_{eH}$	[MPa]	23	23	49	16	42
$\mathbf{R}_{m\ prg.min.\ +N}$	[MPa]	470	470	470	470	470
$\mathbf{R}_{m\ prg.max.\ +N}$	[MPa]	630	630	630	630	630
$\mathbf{R}_{m\ act.\ +N}$	[MPa]	539	542	541	574	551
$\mathbf{R}_{m\ act.\ +NR}$	[MPa]	609	599	608	605	604
$\mathbf{\Delta R}_{m}$	[MPa]	70	57	67	31	53
$\mathbf{A}_{\ prg.min.\ +N}$	[%]	20	20	20	20	20
$\mathbf{A}_{\ act.\ +N}$	[%]	31	29	30	26	27
$\mathbf{A}_{\ act.\ +NR}$	[%]	23	24	26	24	24
$\mathbf{KV}_{2\ prg.avg.min.}$	[J]	27	27	27	27	27
$KV_{2\ act.}$	[J]	219	209	214	225	212
$KV_{2\ prg.ind.min.}$	[J]	19	19	19	19	19
$KV_{2\ (1)+N}$	[J]	219	200	217	221	220
$KV_{2\ (2)+N}$	[J]	226	217	214	231	220
$KV_{2\ (3)+N}$	[J]	213	210	211	224	197
$t_{\ prg.}$	[^{o}C]	-20	-20	-20	-20	-20
$t_{\ act.}$	[^{o}C]	-20	-20	-20	-20	-20
Tensile test	[-]	90	90	90	90	90
Charpy V-notch Test	[^{o}]	0	0	0	0	0
Grain size +N	[^{o}]	10	10	9,5	9	9
Grain size +NR	[^{o}]	10	9,5	9	9	9

Where the abbreviations "act" means actual (measured) value, +N is the value in normalized condition, whereas +NR is value in normalizing rolling, for the following parameters:

R_{eH} : yield strength in [MPa], **R_m** : tensile strength in [MPa]; **A**: elongation on $5.65\sqrt{S_0}$ gauge length in [%]; **KV_2**: The average value of the three test results of absorbed energy; **$KV_{2\,(1)}$** , **$KV_{2\,(2)}$** and **$KV_{2\,(1)}$** : individual absorbed energy.

By comparing the actual values with the specified values in Table 12, it can be seen that the produced materials met all required quality parameters of S355J2+N grade, specified in EN 10025-2 / 2004 standard.

By comparing the measured values of strength (see Table 12) with the predicted values in Table 11, it can be seen that there is a satisfactory agreement. It is very interesting to note that the measured values of the strength in the normalized condition are lower than those in the normalizing rolling condition, which is in accordance with the published results [2-4].

As for example, Fig. 2 shows correlation between measured strength of samples tested in normalized and normalizing rolling condition.

From results shown in Table 12 and Fig.2 it can be seen that a value of yield point in normalized samples was for 16-49 MPa (average of 31 MPa) lower than the values of yield point in a normalizing rolling condition. The results are in a rather good agreement with already published results [2]. The results of tensile strength in normalized condition were for 31-70 MPa (average of 56 MPa) lower than those in normalizing rolling condition.

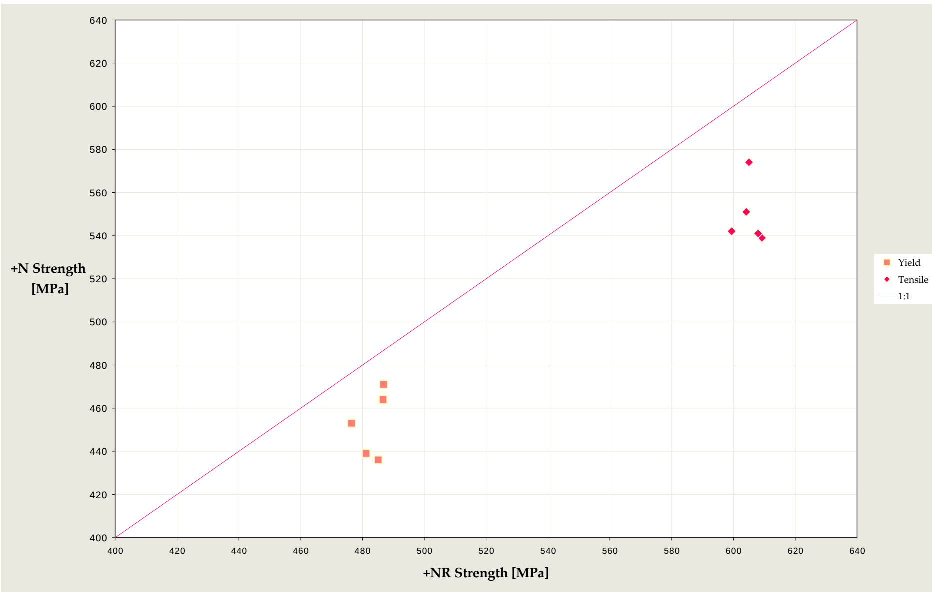

Fig. 2. Comparative correlation between strength in normalized and normalizing rolling condition.

Moreover, it is very interesting to compare typical yield and tensile strength values obtained in Zelezara Smederevo d.o.o material with thickness of 6.00mm, with the same results obtained on a sample of hot-rolled strip with S355J2+N grade, produced at Tata Steel Ijmuiden HSM with thickness of 8.00mmn (Table 13).

Table 13 Comparison between strength values of S355J2+N grade produced in Železara Smederevo d.o.o and Tata Steel Ijmuiden HSM

Materijal	**Condition**	H_{st}	R_{eH+N}	R_{m+N}
Železara Smederevo	+N	6.00	453	549
Tata Steel	+N	8.00	439	523

Bearing in mind that the increase in thickness of the strip of 1mm causes the lowering of yield and tensile strength for approximately 7 MPa and 4 MPa, respectively [5], it may be concluded that there is good agreement.

In order to obtain, at least rough estimation, what might influence of the decline of strength during normalization, microstructure of samples was examined before and after normalization, according to EN ISO 643 2014 testing procedure.

The results in Table 12 demonstrate that the grain size remains practically unchanged. Moreover, the values of observed grain size are in a quite good agreement with those of a sample corresponding to hot-rolled strip quality S355J2+N produced in Tata Steel Ijmuiden HSM (see Table 6).

As for illustration, Figs 3 and 4 show the typical microstructure of materials before and after normalization. The microstructure is ferrite-pearlite, uniform across the thickness and with some pearlitic banding.

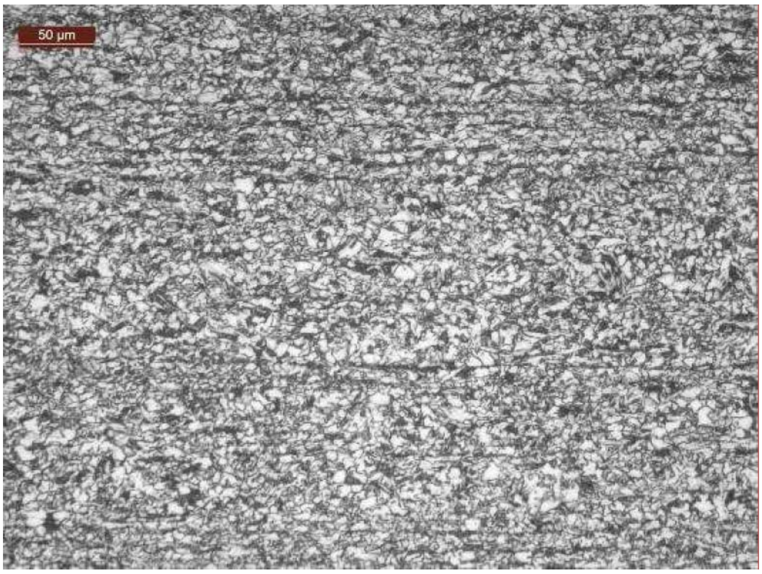

Fig. 3 Typical microstructure obtained on a sample of normalizing rolling material produced at Železara Smederevo d.o.o HSM

The observed microstructure in Fig. 4 corresponds quite well to the microstructure from a sample of hot-rolled strip quality S355J2+N, produced at Tata Steel Ijmuiden HSM (see Fig. 1). It seems that the microstructure of a competitive sample contain something more pearlitic banding, which may be explained by the higher Mn content in the Tata Steel Ijmuiden material.

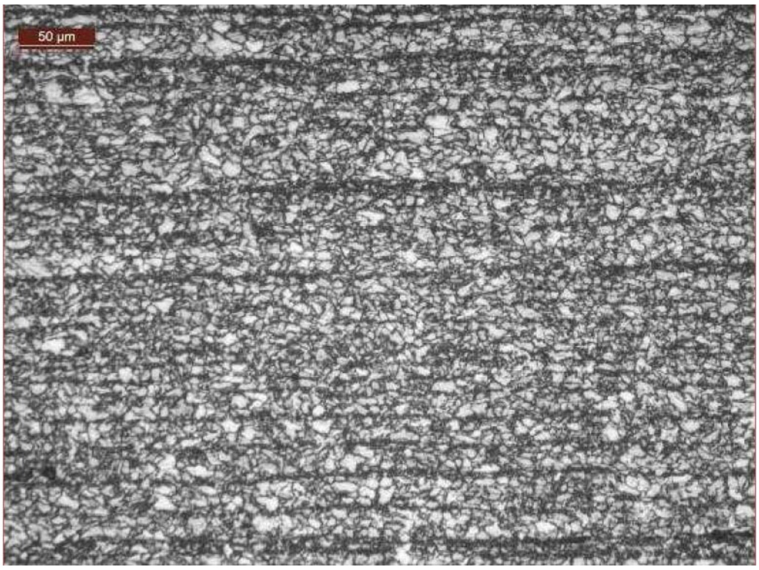

Fig. 4 Typical microstructure obtained on a normalized sample of normalizing rolling materia, produced at Železara Smederevo d.o.o HSM

Since the grain size after normalization remained virtually unchanged, one of the possible reasons for this strength drop is growth of Nb carbonitride precipitation during normalizing.

Conclusions

1. The produced hot-rolled coils in nominal thickness of 6.00mm, met the specified requirements S355J2+N according to quality standard EN 10025-2/2004.
2. The obtained values of strength and microstructural characteristics show quite well agreement with those obtained on competitive material.
3. The obtained values of strength in the normalized condition are lower than those in the normalizing rolling condition.

References

[1] EUROPEAN STANDARD EN 10025-2:2004, ICS 77.140.10; 77.140.45; 77.140.50, Management Centre: rue de Stassart, 36 B-1050 Brussels, 7.

[2] Vereinbarung zur Begutachtung von Erzeugnissen (Band, Blech, Breitflachstahl), die mit geregelter Temperaturführung beim und nach dem Walzen hergestellt werden, zum Nachweis der Gleichwertigkeit mit dem Normalglühen. VdTÜV-Merkblatt Werkstoffe, 3.76 (1976) 1263.

[3] L.Meyer,Microalloying'95, Pittsburgh, ISS 1995, 35.
[4] Antonio Augusto Gorni and Marcos Roberto Soares da Silva, 50th Rolling Seminar – Processes, Rolled and Coated Products, Associação Brasileira de Metalurgia, Materiais e Mineração, Ouro Preto, November 18 to 21, 2013.
[5] G.Vukićević, N.Radović, D.Jeremić, Dj.Drobnjak, Mathematical Modelling of Mechanical Properties of Microalloyed Hot Strip, Proceedings of the Int.Conf on Thermomechanical Processing: Mechanics, Microstructure & Control, Eds. E.J.Palmiere, M.Mahfouf and J.Beynon, 23-26 June 2002 Sheffield , University of Sheffield, 413-417.
[6] G.Vukićević, Mathematical Modelling of Mechanical Properties of Plain Carbon Hot Rolled Strips, unpublished research, ŽELEZARA SMEDEREVO d.o.o, 2002.