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MODELLING OF THE SOLIDIFICATION PROCESS AND THE CHEMICAL HETEROGENEITY OF A 26NiCrMoV115 STEEL INGOT

MODELIRANJE PROCESA STRJEVANJA IN KEMIČNE HETEROGENOSTI INGOTA IZ JEKLA 26NiCrMoV115

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Steel making at ŽĎAS, a.s. using secondary metallurgy technology makes it possible to produce liquid metal with high levels of metallurgical cleanliness. During the casting and subsequent cooling of forging ingots, the steel solidification takes place. Directional material solidification, grain size, chemical heterogeneity and discontinuities can have a negative effect on the products' final properties. The comparison of the chemical composition based on a numerical calculation with the heterogeneity of the real ingot has proven the possibility of using MAGMA software to model the casting and solidification of ingots for open-die forgings made from 26NiCrMoV115 steel.

Key words: forging ingot, solidification, heterogeneity, modelling of segregations

Za uporabo tehnologije sekundarne metalurgije se v ŽĎAS izdeluje tekoče jeklo z veliko metalurško čistostjo. Med ulivanjem in ohlajanjem kovaških ingotov se izvrši strjevanje. Usmerjeno strjevanje, velikost zrn, kemična heterogenost in diskontinuitete lahko negativno vplivajo na lastnosti končnega proizvoda. Primerjava kemične sestave z numeričnim izračunom heterogenosti realnega ingota je dokazala možnost uporabe softvera MAGMA za modeliranje ulivanja in strjevanja ingotov za prosto kovanje iz jekla 26NiCrMoV115.

Ključne besede: kovaški ingot, strjevanje, heterogenost, modeliranje segregacij

1 INTRODUCTION

The manufacture of steel forgings for the rotary parts of gas turbines requires an adherence to exactly defined forming and heat-treatment rules. A prerequisite for the successful production of highly stressed machine parts is a high-quality initial blank or ingot.

The use of MAGMA software to model the ingot casting and solidification, to forecast the internal quality and the segregation of basic alloying elements and to compare the theoretical prerequisites with practical results makes it possible to evaluate the possibility of also using software for other types of numerical simulation related to the processing of ingots.

The evaluation of the chemical heterogeneity of the forging ingot of type 8K8.4 cast at ŽĎAS, a.s. from 26NiCrMoV115 steel demonstrated the requirements for an isotropic structure and mechanical properties of the steel forging are met.

2 MODELLING OF THE INGOT CASTING AND THE SOLIDIFICATION PROCESS

Using the MAGMA software a simulation of the casting and solidification of the 8K8.4 forging ingot in 30NiCrMoV steel with the chemical composition shown in **Table 1** was carried out.

The results of the numerical modelling of the ingot solidification process in the form of the location of the solidus temperature for different solidification times are shown in **Figure 1**. A graphical visualisation of the time

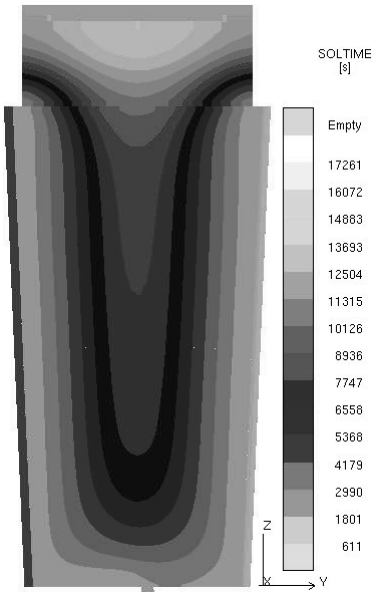


Figure 1: Development of the solidus temperature range depending on time
Slika 1: Časovna evolucija razpona solidusne temperature

Table 1: Chemical composition of steel as per the MAGMA software
Tabela 1: Kemična sestava jekla za softver MAGMA

MAGMA	C	Mn	Si	P	S	Cr	Ni	Cu	Mo	V	Al
	w/%										
30NiCrMoV	0.30	–	–	0.025	0.006	1.40	3.00	–	0.40	–	–

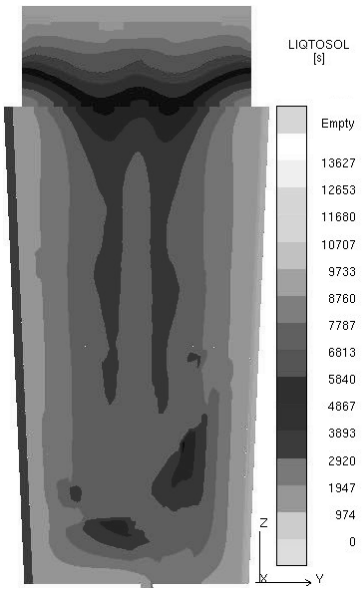


Figure 2: Stay of the melt in the phase boundary between the liquidus and solidus temperatures
Slika 2: Zadržanje taline na fazni meji med likvidusno in solidusno temperaturo

zones when the temperature of the molten steel changes through the phase between the liquidus and solidus lines is shown in **Figure 2**.

The final phase of the solidification process is intended for an immediate share of 100 % solid phase. [1]

Along with the numerical simulation of the ingot casting and the solidification, calculations of the segregation and unmixing of the basic alloying and tramp elements were also carried out. Significant concentration changes throughout the steel ingot's cross-section were only noted for elements with greater content. The concentration distribution of some elements is shown in **Figures 3 and 4**.

It is obvious that the degree of segregation increases from the ingot surface towards the axial part.

The concentration of the elements was deduced from the concentration ranges in **Figures 3 and 4** and arranged in an ascending order, with numbers from 0 to X, according to the local level of concentration. By summing the local content of all the elements the values in **Table 2** were obtained showing the relative segregation degree according to the location of the analyses points in **Figure 5**.

Table 2: Relative segregation degree
Tabela 2: Relativna stopnja segregacije

Sample	1	2	3
H	18	8	0
S	14	9	4
P	7	8	4

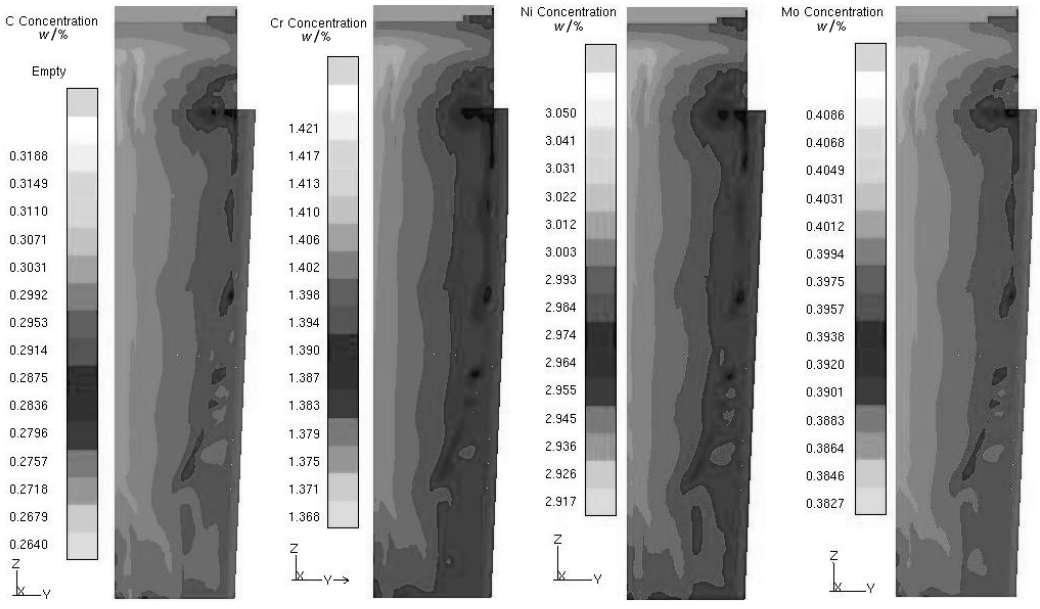
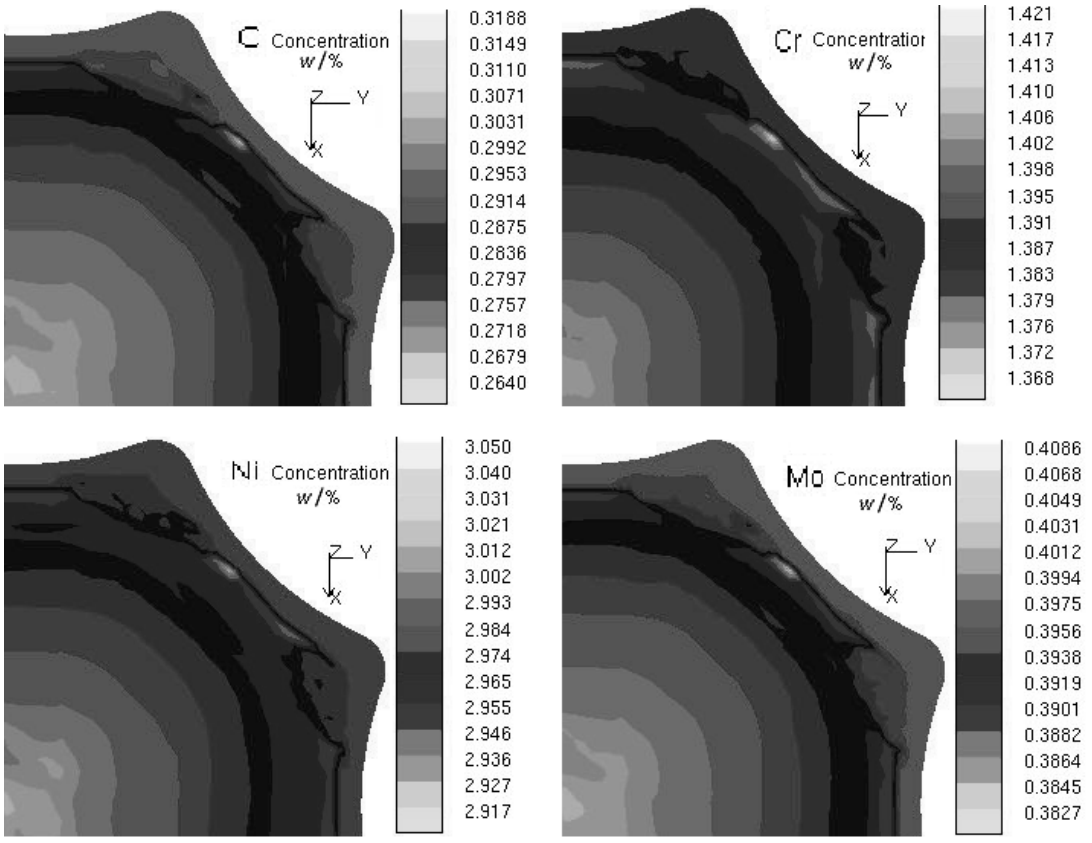


Figure 3: Concentration of some elements in the central vertical section of the ingot
Slika 3: Koncentracija nekaterih elementov na pokončnem prerezu skozi sredino ingota



Cross-section view below the ingot top

Figure 4: Concentration of some elements in the cross-section, view below the ingot top
Slika 4: Koncentracija nekaterih elementov na prerezu pod glavo ingota

Table 3: Chemical composition of steel – final melt test
Tabela 3: Kemična sestava jekla, končna analiza šarže

Melt analyse	C	Mn	Si	P	S	Cr	Ni	Cu	Mo	V	Al	As	Sn	Sb	Ca
	w/%											µg/g			
30NiCrMoV	0.29	0.21	0.01	0.004	0.006	1.69	2.88	0.01	0.41	0.12	0.009	30	<5	<5	4

The highest values of the positive segregation correspond to the ingot part marked with the index H1. Compared with the other sampling points, all the elements attain the maximum concentration here.

The lowest concentrations of the analysed elements were found in H3 and events S3 and P3.

3 PRODUCTION PROCESSING AND SAMPLING METHOD

Within the scope of the experimental work, the 26NiCrMoV115 steel melt with the chemical composition in **Table 3** was made at ŽĎAS, a.s. The molten

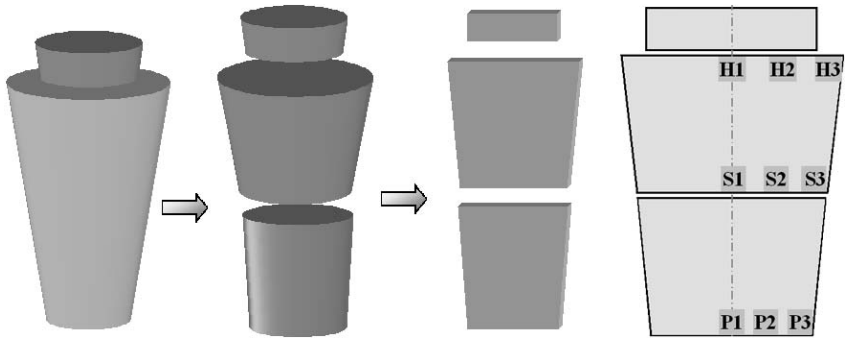


Figure 5: Steel ingot dividing and sampling diagram
Slika 5: Razdelitev ingota in skica odvzema vzorcev

metal was bottom cast in the mould of the 8K8.4 to form an ingot with a mass of approximately 8 tonnes. [3]

The solidification and the cooling of the ingot to ambient temperature took place in the mould. In order to facilitate the manipulation after the fettling, the ingot was divided into three parts using a cutting machine, as shown in **Figure 5**.

Figure 5 shows the sampling points for the specimens taken for analysis from parts below the top, from the middle and from the bottom of the ingot.

4 CHEMICAL COMPOSITION OF THE INGOT IN THE MONITORED ZONES

The samples H1, H2, H3 were cut out from the body part below the ingot top, the samples S1, S2, S3 from the middle part and the samples P1, P2 and P3 from the ingot's bottom part. All the samples were submitted for chemical analyses in the laboratory of ISPAT NOVÁ HUŤ, a.s. and the contents of several elements were determined. [4]

The chemical compositions of the samples, shown in **Table 4**, only include the elements present in sufficient concentrations with respect to the detection limits of the analytical device.

Table 4: Chemical composition of samples taken throughout the ingot cross-section
Tabela 4: Kemična analiza vzorcev, izrezanih iz prereza ingota

Sample	K	H1	H2	H3
C	0,29	0,315	0,292	0,294
Mn	0,21	0,21	0,20	0,20
P	0,004	0,004	0,005	0,004
S	0,006	0,006	0,005	0,006
Cr	1,69	1,67	1,63	1,63
Ni	2,88	2,88	2,80	2,83
Mo	0,41	0,449	0,381	0,405
V	0,12	0,127	0,111	0,117
Al	0,009	0,010	0,010	0,011

Sample	K	S1	S2	S3
C	0,29	0,298	0,289	0,290
Mn	0,21	0,20	0,20	0,20
P	0,004	0,003	0,004	0,004
S	0,006	0,005	0,007	0,006
Cr	1,69	1,62	1,63	1,63
Ni	2,88	2,77	2,82	2,80
Mo	0,41	0,381	0,398	0,396
V	0,12	0,111	0,116	0,116
Al	0,009	0,010	0,010	0,011

Sample	K	P1	P2	P3
C	0,29	0,289	0,289	0,282
Mn	0,21	0,20	0,20	0,20
P	0,004	0,004	0,005	0,004
S	0,006	0,006	0,006	0,006
Cr	1,69	1,62	1,64	1,61
Ni	2,88	2,82	2,83	2,77
Mo	0,41	0,403	0,415	0,409
V	0,12	0,116	0,121	0,117
Al	0,009	0,010	0,010	0,010

If the concentrations of the elements from **Table 4** are arranged in ascending order, with evaluation points from 0 to X according to the increasing content, a sum for all the elements indicating the relative segregation degree in **Table 5** is obtained.

Table 5: Relative segregation degree
Tabela 5: Relativna stopnja segregacije

Sample	1	2	3
H	27	8	18
S	7	11	9
P	10	19	9

In the zone corresponding to the ingot part marked with H1 the highest positive segregations occur. In this area most elements show a significant unmixing. Compared with other sampling points, carbon, chromium, nickel, molybdenum and vanadium attain the maximum segregation; the lowest concentrations of the elements analysed were found in the S1 and also in the S3 and P3 zones.

5 ELEMENT HETEROGENEITY MEASUREMENT

The chemical heterogeneity of the steel samples was determined at VTÚO Brno using a method previously reported [5]. For the energy-dispersion (ED) X-ray microanalysis a JEOL JXA8600/KEVEX Delta V Sesame microscope was used.

The analyses were performed for elements with a content higher than the detection limit for the ED microanalysis. For each analysed element the content was determined for 101 points. The analysed elements were vanadium, chromium, manganese, iron, nickel and molybdenum.

For each point analyses, the program also determined some basic statistical parameters:

X_S mean value
S_X standard deviation
Min minimum value
I_{Het} heterogeneity index $I_{Het} = S_X/X_S$
Max maximum value
I_s segregation index $I_s = Max/X_S$

The results are shown in **Table 6**. For the evaluation of the chemical heterogeneity the maximum point content for each element was considered and obtained along a measured line of 1000 μm for each sample.

The dimensionless parameter known as the segregation index (I_s) was determined as the relationship between the maximum concentration and the average concentration in the given section ($I_s = Max/X_S$). The results are shown in **Table 7**.

Table 6: Basic statistics of samples and elements
Tabela 6: Osnovna statistika vzorcev in elementov

H	H1				H2				H3			
	XS	SX	Min	Max	XS	SX	Min	Max	XS	SX	Min	Max
V	0.096	0.077	0.000	0.593	0.065	0.044	0.000	0.173	0.066	0.052	0.000	0.223
Cr	1.723	0.447	0.959	3.119	1.535	0.370	0.939	3.079	1.464	0.287	0.929	2.269
Mn	0.085	0.095	0.000	0.360	0.146	0.105	0.000	0.400	0.080	0.084	0.000	0.370
Fe	94.72	0.84	91.48	96.31	95.33	0.56	93.82	96.50	95.34	0.48	94.02	96.37
Ni	2.967	0.305	2.301	3.791	2.683	0.269	2.091	3.331	2.865	0.274	2.031	3.611
Mo	0.406	0.269	0.037	1.687	0.239	0.135	0.000	0.667	0.185	0.106	0.000	0.547
S	**S1**				**S2**				**S3**			
	XS	SX	Min	Max	XS	SX	Min	Max	XS	SX	Min	Max
V	0.096	0.146	0.000	1.223	0.067	0.040	0.000	0.173	0.084	0.052	0.000	0.213
Cr	1.561	0.477	0.999	3.119	1.507	0.248	1.119	2.559	1.566	0.239	0.969	2.339
Mn	0.114	0.096	0.000	0.360	0.087	0.089	0.000	0.380	0.147	0.115	0.000	0.410
Fe	95.19	1.13	91.38	96.41	95.25	0.39	94.19	96.04	95.18	0.49	93.54	96.07
Ni	2.729	0.271	2.151	3.551	2.918	0.227	2.351	3.501	2.780	0.264	2.121	3.561
Mo	0.313	0.391	0.000	1.787	0.173	0.096	0.007	0.427	0.241	0.132	0.007	0.797
P	**P1**				**P2**				**P3**			
	XS	SX	Min	Max	XS	SX	Min	Max	XS	SX	Min	Max
V	0.108	0.076	0.000	0.343	0.085	0.048	0.000	0.193	0.071	0.050	0.000	0.213
Cr	1.693	0.481	1.049	3.579	1.603	0.577	1.079	5.129	1.499	0.451	0.829	3.129
Mn	0.221	0.129	0.000	0.480	0.242	0.137	0.000	0.530	0.095	0.083	0.000	0.330
Fe	94.79	0.92	90.42	96.26	95.18	0.70	91.05	96.18	95.26	0.59	93.68	96.31
Ni	2.824	0.283	2.151	3.441	2.688	0.250	2.111	3.261	2.851	0.270	2.331	3.451
Mo	0.370	0.380	0.000	3.147	0.202	0.113	0.017	0.847	0.226	0.140	0.000	0.647

Table 7: I_{Het} and I_s indexes
Tabela 7: Indeks I_{Het} in I_s

H	H1		H2		H3	
	I_{Het}	I_s	I_{Het}	I_s	I_{Het}	I_s
V	0.802	**6.177**	0.677	**2.662**	0.788	**3.379**
Cr	0.259	**1.810**	0.241	**2.006**	0.196	**1.550**
Mn	1.118	**4.235**	0.719	**2.740**	1.050	**4.625**
Fe	0.009	**1.017**	0.006	**1.012**	0.005	**1.011**
Ni	0.103	**1.278**	0.100	**1.242**	0.096	**1.260**
Mo	0.663	**4.155**	0.565	**2.791**	0.573	**2.957**
S	**S1**		**S2**		**S3**	
	I_{Het}	I_s	I_{Het}	I_s	I_{Het}	I_s
V	1.521	**12.740**	0.597	**2.582**	0.619	**2.536**
Cr	0.306	**1.998**	0.165	**1.698**	0.153	**1.494**
Mn	0.842	**3.158**	1.023	**4.368**	0.782	**2.789**
Fe	0.012	**1.013**	0.004	**1.008**	0.005	**1.009**
Ni	0.099	**1.301**	0.078	**1.200**	0.095	**1.281**
Mo	1.249	**5.709**	0.555	**2.468**	0.548	**3.307**
P	**P1**		**P2**		**P3**	
	I_{Het}	I_s	I_{Het}	I_s	I_{Het}	I_s
V	0.704	**3.176**	0.565	**2.271**	0.704	**3.000**
Cr	0.284	**2.114**	0.360	**3.200**	0.301	**2.087**
Mn	0.584	**2.172**	0.566	**2.190**	0.874	**3.474**
Fe	0.010	**1.016**	0.007	**1.011**	0.006	**1.011**
Ni	0.100	**1.218**	0.093	**1.213**	0.095	**1.210**
Mo	1.027	**8.505**	0.559	**4.193**	0.619	**2.863**

Table 8: Maximum and minimum segregation indexes
Tabela 8: Največji in najmanjši indeksi segregacije

Maximal and minimal segregation idexes

H1	H2	H3
S1	S2	S3
P1	P2	P3

	V	
6.18	2.66	3.38
12.74	2.58	2.54
3.18	2.27	3.00

	Mn	
4.24	2.74	4.63
3.16	4.37	2.79
2.17	2.19	3.47

	Ni	
1.28	1.24	1.26
1.30	1.20	1.28
1.22	1.21	1.21

	Cr	
1.81	2.01	1.55
2.00	1.70	1.49
2.11	3.20	2.09

	Fe	
1.02	1.01	1.01
1.01	1.01	1.01
1.02	1.01	1.01

	Mo	
4.16	2.79	2.96
5.71	2.47	3.31
8.51	4.19	2.86

Table 9: Mass distribution of segregation indexes
Tabela 9: Razdelitev indeksov segregacije po masi

Maxima				Minima		
H1	H2	H3		H1	H2	H3
S1	S2	S3		S1	S2	S3
P1	P2	P3		P1	P2	P3
1	0	1		0	0	0
2	0	0		0	3	1
1	1	0		1	1	0

In order to make it easier to understand, the segregation index for the analysed elements is arranged so that it emphasizes the maximum and minimum segregation index. According to the position of the samples in the ingot, the following indexes were determined.

The distribution of the values of the maximum and minimum segregation indexes of the elements shows that it is not possible to decide unambiguously in which ingot part the highest and/or lowest segregation intensity occurs.

If we assign the same weight to the highest and/or the lowest segregation index of each element (six analysed elements with a mass of 1/6), the distribution of the maximum and/or minimum segregation indexes of the elements, the data in **Table 8**, are obtained.

Table 10: Limit values of the segregation indexes related to the elements
Tabela 10: Mejne vrednosti za indekse segregacije za elemente

Maxima		
H1	H2	H3
S1	S2	S3
P1	P2	P3
Fe		Mn
V Ni		
Mo	Cr	

Minima		
H1	H2	H3
S1	S2	S3
P1	P2	P3
	Fe Ni Mo	Cr
Mn	V	

These data show that the highest segregation index is obtained in the ingot axis area, where a fraction of 4/6 of cases falls on the vertical column of samples H1-S1-P1

The smallest segregation index is found for samples from the S2 ingot position. In terms of the fraction 3/6 it means S2 takes half of all cases. The fraction 2/3 of cases falls on the column H2, S2 and P2.

The minimum fraction 1/6 of the lowest measured values of the segregation indexes falls on the vertical columns H1–S1–P1 and H3–S3–P3, while in the column H1–S1–P1 the weight of occurrence of the elements with the maximum heterogeneity index is 2/3. It can be concluded that the highest unmixing tendency is expected in the ingot axis – column 1. The lowest unmixing tendency can be expected at the surface of the ingot – column 3.

The segregation behaviour of the elements Cr and Mn is different, as shown in **Table 9**.

The smallest measured segregation indexes are found for the ingot areas H2, S2 and P2. However, there are also two exceptions to this rule, again the elements are Cr and Mn.

Sequence according to the highest segregation index:

Table 11: Sequence of segregation indexes
Tabela 11: Sekvence indeksov segregacije

Segregation	V	Mo	Mn	Cr	Ni	Fe
Index	12.74	8.51	4.63	3.20	1.30	1.02

Sequence of elements according to the lowest segregation index:

Segrgeation	Mo	V	Mn	Cr	Ni	Fe
Index	2.47	2.27	2.17	1.49	1.20	1.01

Both sequences are almost identical, i.e., Mo, V, Mn, Cr, Ni and Fe and only two elements, molybdenum and vanadium, exchange their places in the sequence.

In both sequences the elements V, Mo and Mn are in the first three places and the sequence is ended by the elements Cr, Ni and Fe. The reciprocal value of the segregation index $k \approx 1/I_s$ represents, as a first approximation, the effective distribution coefficient of the element [6].

6 CONCLUSION

The relatively good agreement of the results of the measurements and the simulations of the maximum and minimum segregation index sequence indicate the same tendencies during the solidification and cooling of a steel ingot with a given chemical composition.

On the basis of the measurements it can be concluded that this tendency depends on the real value of the effective distribution coefficient of the elements. It is also possible to conclude on the basis of the measurements that, of the external parameters, the parameter referred to as the local solidification time plays an important role, i.e., the time when the particular measured area of the sample stays between the solidus and liquidus temperatures.

The use of the MAGMA software to model the ingot casting and solidification process and to predict the behaviour of the basic alloying elements confirms the relative agreement between the theoretical predictions and the practical results.

The determination of the chemical heterogeneity of the forging ingot type 8K8.4 of 26NiCrMoV115 steel will contribute to an explanation of the causes of possible occurrence of structural anisotropy of the steel in connection with the end-use properties.

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