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EVALUATION OF EN AW-5083 ALUMINUM ALLOY HOMOGENEITY USING STATISTICAL ANALYSIS OF MECHANICAL PROPERTIES

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Abstract

In the frame of this investigation, the homogeneity of six (6) ingots of aluminum alloy EN AW-5083 cast by semi-continuous vertical Direct Chill casting (DC) Process was investigated correlating mechanical properties in as-cast and homogenized condition. The investigation followed the static design of the Latin square. Determination of the ultimate tensile strength and elongation across the cross-sectioned sliced at the ingots' fronts and rears in as-cast state revealed differences per cross section of each particular slice. Comparison of obtained differences enabled evaluation of mechanical properties homogeneity of the ingots as a whole. The influence and significance of homogenization was also quantified correlating the mechanical properties results for as-cast and homogenized state at the front and rear position in ingot. The results were processed using the StatSoft® STATISTICA 13.2 software package using charge, slice height and slice width as sources of variability. Comparison of obtained statistical results for both states respectively in respect to the sampling position enabled estimation of homogenization process influence on mechanical properties.

Keywords: *Aluminium Alloy EN AW-5083; Direct Chill Process; Ultimate Tensile Properties; Elongation.*

1. Introduction

EN AW-5083 alloy have found great applications in the automotive, aviation, spaceflight, marine, packaging, and construction industries due to their special characteristics, such as good weldability, ductility, toughness, formability, and corrosion resistance [1, 2]. An imperative for aluminium 5xxx alloys is achieving the high mechanical properties based on grain refinement. Thermomechanical processes by recrystallization or homogenization are therefore important factor in order to achieve isotropic mechanical properties in the ingot as a whole. Thermomechanical behaviour of EN AW-5083 alloy significantly depends from the heat treatment temperature and procedure [3-7]. Microstructure development followed by obtained mechanical properties is significantly dependent from the commonly present elements interaction as well as from those introduced by melt treatment [8-10]. Thermomechanical treatment also influences the corrosion resistance [11].

DC casting was invented independently by VAW (Germany) and Alcoa (USA) and was an essential technological evolution to improve the quality of large castings which were originally produced using book, or permanent mould [12]. During DC casting, liquid metal is poured into a water-cooled mould (primary cooling) [13, 14]. While the skin of the ingot becomes solid, the inside still remains semi-solid/liquid. Further cooling of the ingot bulk is achieved by quenching the solid shell directly using water jets (secondary cooling). The cooling rate (dT/dt) varies from 1 K/s in the centre of the ingot to around 20 K/s in its surface zone [13]. The phases formed in the different zones of the ingot depend on their chemical composition and cooling rate. Furthermore, the extrusion formability as well as the mechanical properties and surface extruded properties depend on the chemical composition and degree of homogeneity of the ingot.

Maintaining the homogeneity of the as-cast structure is essential for ingots made of high-quality wrought aluminium alloys because fine, equiaxed grain structure and uniformly precipitated intermetallic phases warrant numerous technological and economic advantages. The most important among those are improved mechanical properties, enhanced ability for heat treatment and formability during subsequent processing by rolling or extrusion, fewer surface defects, and diminished propensity for occurrence of hot and cold tears in the outer regions of the ingot [15, 16]. The addition of grain refining agents and optimization of casting parameters are aimed at inhibiting the growth of columnar crystals at the ingot edge and in general, at achieving uniformity

Dedicated to the memory of Professor Dragana Živković

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of ingot cross-sectional structure, that is, a broad zone of equiaxed crystals [17]. A fine-grained microstructure is dependent on the availability of numerous and potent heterogeneous nuclei, on the presence of a solute element for constitutional undercooling, and on solidification conditions, in particular the cooling rate [18].

The uniformity of as-cast microstructure and chemical composition, and thus the improvement of mechanical and physical properties, before deformation processes, is carried out by homogenizing the ingots cast by the semi-continuous vertical Direct Chill casting Process [19].

In this study, influence of heat treatment process was evaluated using statistical analysis in order to correlate obtained mechanical properties results in as-cast and homogenized state as a consequence of microstructural change. Comparison of the obtained results enabled the homogeneity of the ingots' front and rear sections (slices) properties determination, their mutual comparison and thus the estimation of homogeneity as a whole. Correlation of the results in both as-cast and homogenized state enables quantification of variability source (charge, slice height/width) and their influence on homogeneity of the ingots as a whole.

2. Methodology

Investigation of mechanical properties homogeneity was carried out in six ingots cast by the Direct Chill Process. The ingots 1430 x 520 x 5100 mm in size were manufactured from six different charges of alloy EN AW-5083 (designations 3112, 3113, 3114, 3116, 3117, 3120). Before casting, the melt was refined with an argon and chlorine mixture in an Alpur unit. For grain refinement, the Al-Ti5-B1 master alloy was used in an average amount of 1.9 kg/t melt in the following procedure: small bars of the master alloy were added to the casting furnace, and a master alloy wire was introduced in a launder positioned in front of the Alpur unit [20].

Investigation model plan was based on "Latin square" [21]. The model of the investigation plan is one of the orthogonal models of experiments, in which no interactions between sources of variability - process factors are expected. Since ingot dimensions (length, width, and height) are potential sources of variability, without mutual interaction, this model is applicable for ingot homogeneity investigation.

Main cause of inhomogeneity and variability is considered to be melt charge. Within the charges the influence of the particular slice dimension as a source of variability is assumed (slice height *i* and slice width *j*).

Figure 1 is a schematic representation of the Latin square based sampling design where *i* is slice height/ingot depth, and *j* is slice width/ingot width. The specimens cut from the slice carry the following designation: specimen number, letters F (ingot front section) or R (ingot rear section), condition C (as-cast) or H (homogenized).

Heat treatment is carried out in the push type furnace for homogenization, where ingots are pushed through the furnace in the vertical position. Previous experience [22] suggests that material retention should be fully achieved during the 8-10 hours at 520 °C in homogenization process for the EN AW-5083 alloy. In order to verify the effect of the homogenization process on the ingot properties, homogenization in the semi-industrial conditions in salt bath AVS250 Durferrit was carried out at 520 °C in duration of 10 hours.

Homogeneity investigation of samples in as-cast condition (C) were carried out at the lower half of the board, while the homogenized condition (H) was tested on samples taken from identical, mirror-symmetric places form upper half of the plates [20].

From each of the as-cast and homogenized sections, 36 samples from the ingots' fronts and rears respectively were taken according to the statistical design of the experiment. Two parallel samples A and B for mechanical properties investigation (ultimate tensile strength *UTS* and elongation A_{50}) from every designated position. Test samples were prepared according to the EN 10002-1 norm [23], and the mean value of results was taken.

Mechanical properties investigations were performed on AMSLER testing machine, type 10THZ722, with maximum stretching force up to 100 kN.

Processing of mechanical properties result in as-cast and homogenized state has been performed using StatSoft® Statistica 13.2 program. Statistical analysis has been based on regression analysis (*F*-Test) in order to define if the means between two populations are

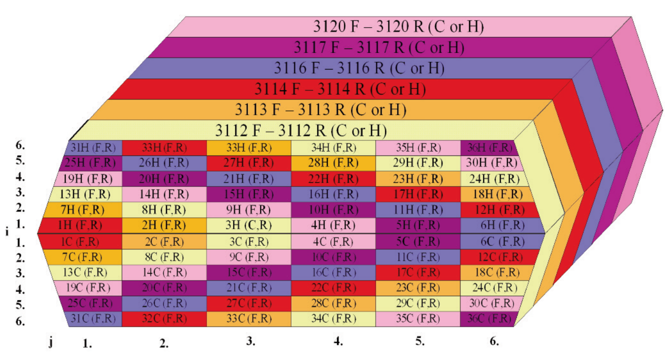


Figure 1. *Sampling from EN AW-5083 ingots following the Latin square experiment design*

significantly different. *P* value is used for defining the area in the tail of a probability distribution. *P* value indicates the hypothesis acceptance and therefore variability source influence. Performed statistical analysis enables the comparison of mechanical properties for the ingots' fronts and rears as well as comparison at indicated positions on particular slice. Comparison of obtained results for both states respectively enabled estimation of homogenization influence on mechanical properties. The major outcome of obtained properties fluctuation is possibility of quantitative prediction of feature behaviour in whole ingot.

Table 1. *Results of measurement of ultimate tensile strength UTS, elongation A_{50} and number of grains per unit area N_A of samples in as-cast state alloy EN AW-5083*

Sample Number	$\overline{UTS}$/ MPa	$\overline{A_{50}}$/ %	$\overline{N_A}$/ No./mm²	Sample Number	$\overline{UTS}$/ MPa	$\overline{A_{50}}$/ %	$\overline{N_A}$/ No./mm²
1FC	251.5	19	69.92	1RC	253	18.5	85.11
2FC	248	22	45.36	2RC	239.5	17	27.81
3FC	217	12.5	53.03	3RC	218	11	27.04
4FC	245	19	37.79	4RC	246.5	18	53.49
5FC	225	11.5	42.87	5RC	202.5	8.5	16.1
6FC	237.5	12.5	61.52	6RC	223	10	50.72
7FC	259.5	22.5	70.73	7RC	254.5	19	69.29
8FC	227	14	47.28	8RC	219.5	11.5	42.96
9FC	259	19.5	42.38	9RC	257	19	54.75
10FC	228	12	43.52	10RC	223	10.5	21.34
11FC	228.5	11	50.64	11RC	216	9	42.27
12FC	252	19	51.7	12RC	246.5	15.5	53.82
13FC	237	15	63.44	13RC	232	16	74.2
14FC	263.5	19.5	45.75	14RC	260	21.5	67.16
15FC	238	14	48.21	15RC	228.5	11.5	28.41
16FC	236.5	14	51.82	16RC	226.5	11	53.44
17FC	250	20.5	53.16	17HC	247	15.5	59.12
18FC	258.5	23.5	68.86	18RC	257.5	20	60.46
19FC	265.5	22	84.91	19RC	263.5	24	74.41
20FC	243.5	15.5	73.48	20RC	235	12.5	43.4
21FC	238	13	59.17	21RC	210.5	9	56.14
22FC	254	18	61.4	22RC	251.5	16.5	66.72
23FC	260.5	21.5	55.28	23RC	260	21.5	69.31
24FC	240	14.5	67.84	24RC	236.5	9.5	69.58
25FC	251.5	19	64.35	25RC	241.5	14	50.56
26FC	248.5	16	77.65	26RC	230	12.5	57.12
27FC	261	20.5	74.61	27RC	255.5	19.5	99.35
28FC	263	23.5	71.26	28RC	264	22	79.51
29FC	247	15.5	79.42	29RC	240.5	10.5	90.81
30FC	265.5	23.5	80.43	30RC	263	21	82.26
31FC	253	19.5	78.75	31RC	248.5	14.5	82.13
32FC	260.5	24	93.14	32RC	257.5	20.5	128.49
33FC	261.5	23	83.14	33RC	270	23	81.59
34FC	252.5	18	80.03	34RC	245	15.5	125.86
35FC	264.5	24.5	108.7	35RC	266	23.5	106.32
36FC	257.5	20	86.55	36RC	243	14.5	66.75

3. Results and discussion

Chemical analysis of examined charges of alloy EN AW-5083 is given in previous investigation [20, 24]. Number of grains per unit area effect on significant source of variability, respectively to the ingot fronts and rears indicates small variation per charge and similar behaviour relating the slice height and width in both conditions [20, 24, 25]. Results of the ultimate tensile strength *UTS*, elongation A_{50} and grain size per unit area N_A for as-cast and homogenized samples are given in Table 1 and 2.

Table 2. *Results of measurement of ultimate tensile strength UTS, elongation A_{50} and number of grains per unit area N_A of samples in homogenized state alloy EN AW-5083*

Sample Number	$\overline{UTS}$/ MPa	$\overline{A_{50}}$/ %	$\overline{N_A}$/ No./mm²	Sample Number	$\overline{UTS}$/ MPa	$\overline{A_{50}}$/ %	$\overline{N_A}$/ No./mm²
1FH	266	26	84	1RH	258.5	18.5	87.68
2FH	255	21.5	45.78	2RH	249	20	38.81
3FH	248.5	20	54.36	3RH	234	15.5	41.13
4FH	256	21	46.73	4RH	258	23	37.49
5FH	256.5	23	52.84	5RH	237	18	22.07
6FH	269.5	29	75.5	6RH	261.5	19	96.75
7FH	264.5	23	81.36	7RH	265.5	23	75.34
8FH	264	22	54.54	8RH	242	18	47.39
9FH	258	20.5	48.86	9RH	265	18	57.16
10FH	256.5	22	53.79	10RH	250	19	37.83
11FH	260	24	55.9	11RH	255	18	66.74
12FH	263	26	74.03	12RH	261.5	22.5	65.08
13FH	266	22	66.12	13RH	267.5	22.5	85.43
14FH	269	25	59.98	14RH	252	23	58.73
15FH	267.5	24	58.81	15RH	257.5	22	37.85
16HF	264	24.5	53.79	16HR	269.5	22	79.31
17HF	260.5	23.5	61.6	17RH	260.5	23	57.51
18FH	267.5	25	80.1	18RH	267.5	25.5	86.04
19FH	273	28	81.16	19RH	274.5	27	77.75
20FH	271.5	26	76.74	20RH	265	26	53.49
21FH	270.5	23	73.4	21RH	277.5	24	82.56
22FH	269	27	79.62	22RH	270	23	79.46
23FH	264	28	78.38	23RH	264.5	27	82.42
24FH	269.5	26.5	81.57	24RH	270.5	26	80.48
25FH	277	26	89.22	25RH	274	26	60.65
26FH	280	29	100.12	26RH	283	24.5	91.24
27FH	272.5	26	94.63	27RH	277	25.5	119.81
28FH	273	28	88.76	28RH	276.5	25	95.38
29FH	275	28	102.69	29RH	269	27	111.59
30FH	276	26.5	81.76	30RH	277.5	33	95.93
31FH	278	29	101.9	31RH	279.5	31	91.26
32FH	270	28	101.78	32RH	272	26.5	141.19
33FH	271.5	26.5	114.04	33RH	273	27	96.94
34FH	277	25.5	104.01	34RH	273.5	29.5	110.67
35FH	277	28.5	92.51	35RH	277.5	27	105.46
36FH	282	29	88.19	36RH	282	27	68.06

Comparison of EN AW-5083 alloy samples in as-cast and homogenized state on characteristic positions with significantly different cooling conditions resulted in differentiation of grain numbers per unit area. In order to emphasis the microstructure development influence on investigated mechanical properties two characteristic positions in both states respectively as-cast and homogenized and from the same positions (front and rear) has been presented by micrographs in Figure 2.

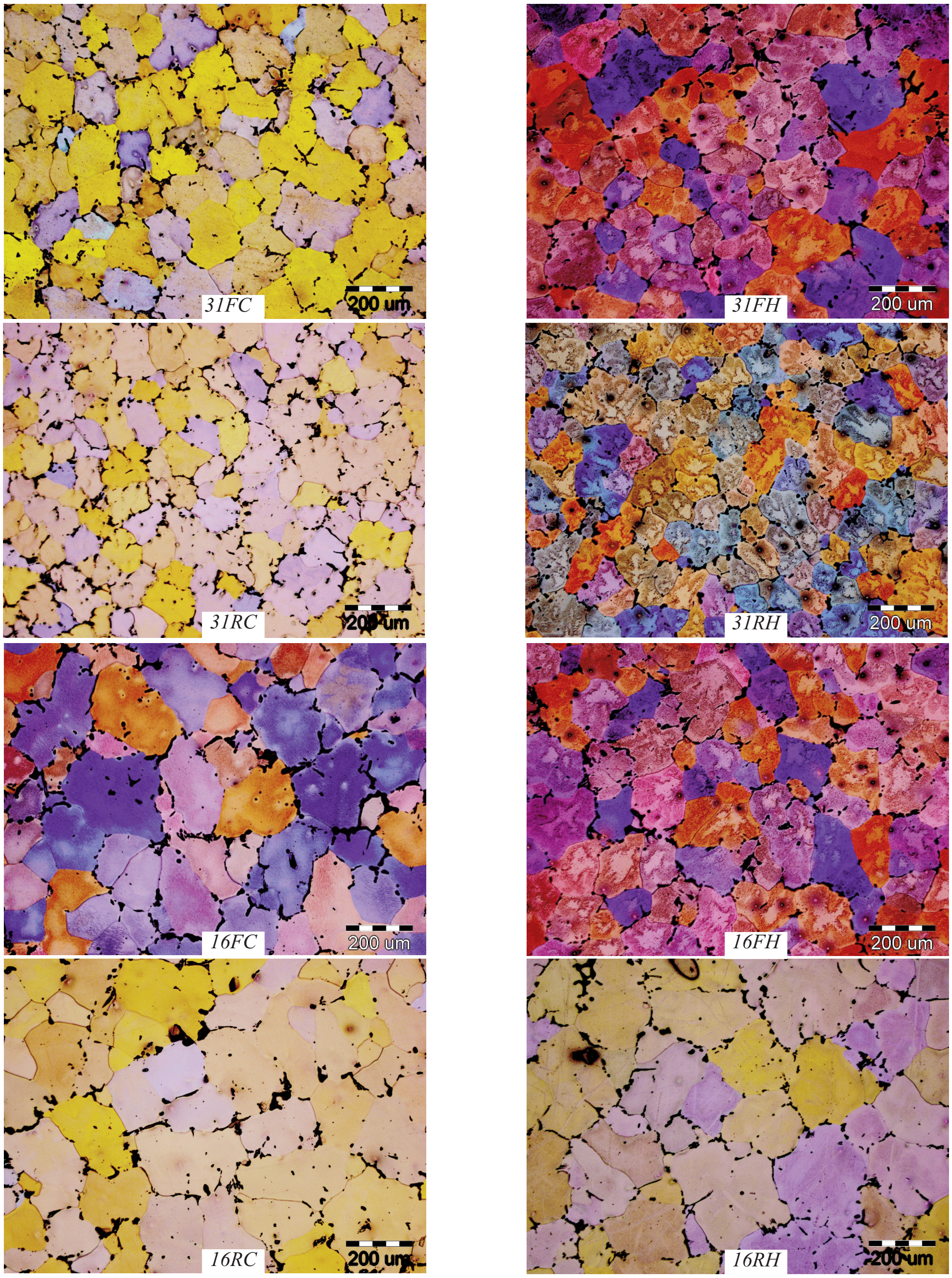


Figure 2. *Micrographs of EN AW-5083 alloy samples from characteristic positions at ingot front (F) and rear (R) positions, and in both states respectively (as-cast C, homogenized H)*

Number of grains per unit area significantly depends from local cooling parameters and therefore from the position in charge and ingot respectively. Samples 31 and 16 belong to charge 3116 according to the Figure 1. Edge samples 31 at front (F) and rear (R) positions indicated different number of grains per unit area 78.75 No./mm^2 and 82.13 No./mm^2 in as-cast state (C) and 101.90 No./mm^2 and 91.26 No./mm^2 in homogenized state (H). Front position is related to higher cooling rates due to intensive thermal gradient and start of solidification. Beside this, position of the sample 31 is subjected to the intensive interaction with the bulk melt and the high mould - melt temperature gradient which also comprehend to the higher numbers of grains per unit area. Inner samples 16 at front and rear positions indicated slightly different numbers of grains per unit area 51.82 No./mm^2 and 53.44 No./mm^2 in as-cast state and 53.78 No./mm^2 and 79.31 No./mm^2 in homogenized state. Samples 16 do not reveal significant difference in number of grains per unit area which indicates isotropic thermal conditions at investigated position.

2.1. Influence of individual variables on ultimate tensile strength

Figure 3 is graphic representations of the relationship between the individual variables (charge, slice height/ingot depth and slice width/ingot width) and *the mean ultimate tensile strength in as-cast state* in EN AW-5083 specimens.

Graphic representation of the relationship between individual variables and mean ultimate tensile strength in as-cast state for the:

a) ingot front section

- The effect of the *charge* shows large variations of ultimate tensile strength in both directions in relation to the total arithmetic mean for the ingot front ($\overline{UTS}_{FC}$ = 248.99 MPa);
- The influence of the *slice height (i)* shows deviation of ultimate tensile strength from total arithmetic mean as a very pronounced increase from -11.6528 MPa for i = 1 (ingot centre) with standard deviation of 13.7028 to +11.6806 MPa for i = 6 (ingot edge) with standard deviation 7.50777;
- The influence of the *slice width (j)* indicates deviation of ultimate tensile strength from total arithmetic mean with the parabolic trend with minimum of -2.4861 MPa with standard deviation of 12.72006 positioned in middle slice section (j = 4) and maximum at the slice edge of +4.0139 MPa (j = 1) with standard deviation of 9.58123.

b) ingot rear section

- The effect of the charge shows large variations of ultimate tensile strength in both directions in relation to the total arithmetic mean for the ingot rear section ($\overline{UTS}_{RC}$ = 242.56 MPa);
- The influence of the *slice height (i)* shows deviation of ultimate tensile strength from total arithmetic mean as a very pronounced increase from -12.1389 MPa for i = 1 (ingot centre) with standard deviation of 19.18181 to +12.4444 MPa for i = 6 (ingot edge) with standard deviation of 11.30044;
- The influence of the *slice width (j)* indicates deviation of ultimate tensile strength from total arithmetic mean with the parabolic trend with minimum of -3.8889 MPa with standard deviation of 24.88708 positioned in edge-inner part of the slice (j = 5) and maximum at the edge of the slice +6.2778 MPa (j = 1) with standard deviation of 10.97117.

The variance analysis is variability analysis between the means, expressed as the variance. The results obtained by the *F*-Test for the ultimate tensile strength for the ingots' front and rear sections in as-cast state are shown in Table 3.

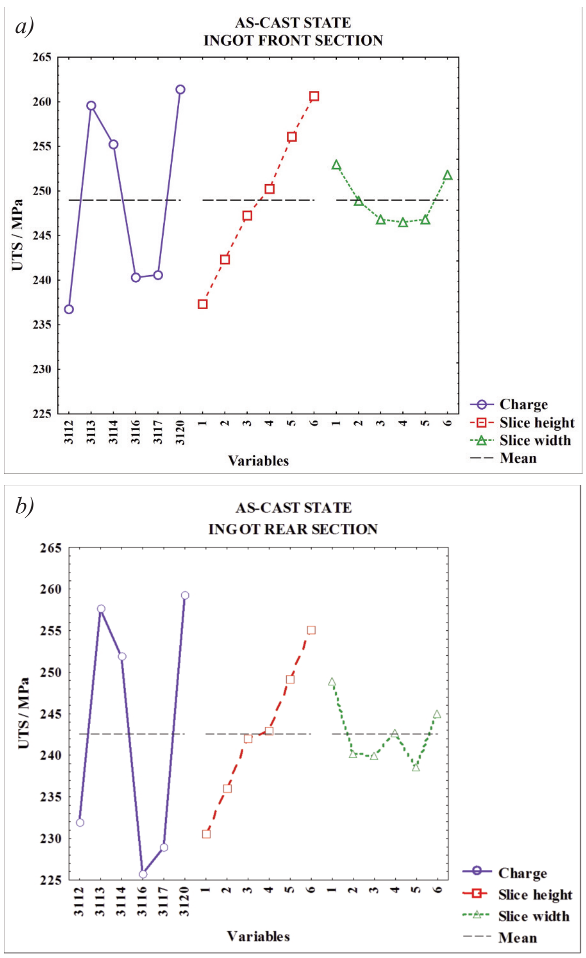


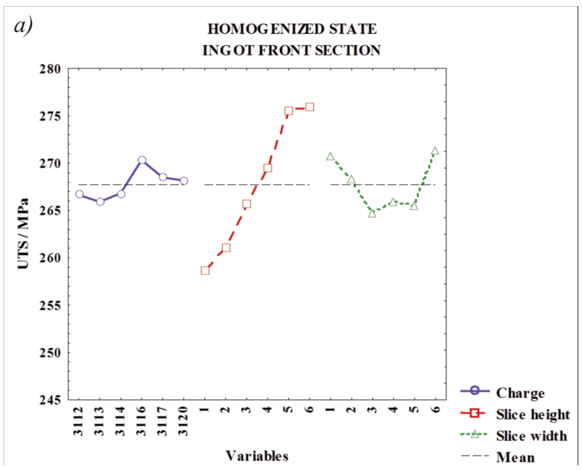
Figure 3. *Graphic representation of the relationship between individual variables and mean ultimate tensile strength (as-cast state) a) ingot front section; b) ingot rear section*

Table 3. *Analysis of variance of the Latin square for the ultimate tensile strength - ingots' front and rear sections - as-cast state*

Variables	Sum of Squares		Degrees of Freedom		Mean Squares		*F*-Test		Significance *P*	
	F	R	F	R	F	R	F	R	F	R
Charge	*3607.535*	*7050.222*	*5*	*5*	*721.507*	*1410.044*	*41.06601*	*38.29619*	*0*	*0*
Slice height	*2228.785*	*2323.222*	*5*	*5*	*445.7569*	*464.644*	*25.37115*	*12.61954*	*0*	*1.3e-005*
Slice width	238.035	434.555	5	5	47.6069	86.911	2.70964	2.36047	0.050077	0.077354
Residual	351.389	736.389	20	20	17.5694	36.819				

From Table 3, where the results of variance analysis are given for the ingot front and rear, it is evident that the differences in the ultimate tensile strength are highly significant in respect to *charge* and *slice height* due to significance value ($P < 0.05$), whereas *slice width* appear to be minor variability sources.

Figure 4 is graphic representation of the relationship between the individual variables (charge, slice height/ingot depth and slice width/ingot width)



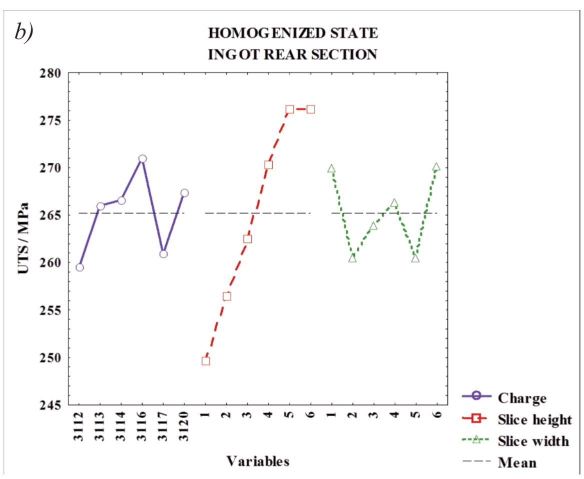


Figure 4. *Graphic representation of the relationship between individual variables and mean ultimate tensile strength (homogenized state) a) ingot front section; b) ingot rear section*

and *the mean ultimate tensile strength in homogenized state* in EN AW-5083 specimens.

Graphic representation of the relationship between individual variables and mean ultimate tensile strength in homogenized state for the:

a) ingot front section

- The effect of the *charge* shows small variations of ultimate tensile strength in both directions in relation to the total arithmetic mean for the ingot front ($\overline{UTS}_{,PH}$ = 267.74 MPa);
- The influence of the *slice height (i)* shows deviation of ultimate tensile strength from total arithmetic mean as a very pronounced increase from -9.15278 MPa for i = 1 (ingot centre) with standard deviation of 7.74220 to +8.18056 MPa for i = 6 (ingot edge) with standard deviation of 4.43189;
- The influence of the *slice width (j)* indicates deviation of ultimate tensile strength from total arithmetic mean the parabolic with the parabolic trend with minimum of -2.98611 MPa with standard deviation of in middle slice section (j = 3) and maximum at the edge of the slice +3.51389 MPa (j = 1, 6) with standard deviation of 6.72867.

b) ingot rear section

- The effect of the charge shows large variations of ultimate tensile strength in both directions in relation to the total arithmetic mean for the ingot rear section ($\overline{UTS},_{KH}$ = 265.22 MPa);
- The influence of the *slice height (i)* shows deviation of ultimate tensile strength from total arithmetic mean a very pronounced increase from -15.5556 MPa for i = 1 (ingot centre) with standard deviation of 11.77993 to +11.0278 MPa for i = 6 (ingot edge) with standard deviation of 4.03423;
- The influence of the *slice width (j)* indicates deviation of ultimate tensile strength from total arithmetic mean with similar parabolic trend with minimum of -4.7222 MPa with standard deviation of 15.52740 positioned in edge-inner part of the charge (j = 2, 5) and maximum at the edge of the charge +4.8611 MPa (j = 1, 6) with standard deviation of 8.38103.

The results obtained by the *F*-Test for the ultimate tensile strength for the ingot front and rear sections in homogenized state are shown in Table 4.

Table 4. *Analysis of variance of the Latin square for the ultimate tensile strength - ingots' front and rear sections - homogenized state*

Variables	Sum of Squares		Degrees of Freedom		Mean Squares		*F*-Test		Significance *P*	
	F	R	F	R	F	R	F	R	F	R
Charge	76.701	*557.389*	5	*5*	15.3403	*111.4778*	1.10972	*3.88782*	0.386509	*0.012653*
Slice height	*1590.035*	*3560.639*	*5*	*5*	*318.0069*	*712.1278*	*23.00462*	*24.83565*	*0*	*0*
Slice width	*233.535*	*552.222*	*5*	*5*	*46.7069*	*110.4444*	*3.37878*	*3.85178*	*0.022521*	*0.013169*
Residual	276.472	573.472	20	20	13.8236	28.6736				

The *UTS* variance analysis for the homogenized ingots' front, Table 4, shows significant differences in *slice height* and *width* based on significance *P* ($P < 0.05$), while the source of *charge* variability did not show significant influence based on significance *P* ($P = 0.386509$). The *UTS* variant analysis for the homogenized ingot rear shows a significant difference for all three variability sources *slice height, slice width* and *charge*.

After the homogenization process was performed, a significant increase in ultimate tensile strength was observed for all investigated samples, and thus the total mean value in as-cast state increases from $\overline{UTS}_{,C} = 245.78$ MPa to $\overline{UTS}_{,H} = 266.48$ MPa in homogenized state. The decrease of the total mean coefficient of ultimate tensile strength variation in as-cast stat $\bar{V}_{,UTS\text{-}C} = 4.00$ % [14], to $\bar{V}_{,UTS\text{-}H} = 3.79$ % in homogenized state was also determined, which indicates a uniform distribution of ultimate tensile strength, both through the cross-sectioned slices, as well as through the ingot as a whole. Correlation coefficients for the ultimate tensile strength between the ingots' fronts and rears and different charges $r_{c,CF\text{-}CR}$ *(UTS, 3112-3120)* and $r_{c,HF\text{-}HR}$ *(UTS, 3112-3120)*, for both as-cast and homogenized state, shown in Table 5, indicate a high ultimate tensile strength homogeneity within each particular ingot. From the resulting total correlation coefficient for ultimate tensile strength for the as-cast ($\overline{r}_{c,CF\text{-}CR}$ *(UTS)= 0.94)* and homogenized state ($\overline{r}_{c,HF\text{-}HR}$ *(UTS)= 0.84*), indicated also in Table 5, high degree of correlation between the ingots' front and rears indicates the total homogeneity of the ultimate tensile strength within all homogenized ingots.

Table 5. *Correlation coefficients for the ultimate tensile strength for investigated charge samples in as-cast* $r_{c,CF\text{-}CR}$ *(UTS) and homogenized state* $r_{c,HF\text{-}HR}$ *(UTS) and total correlation coefficient* $\overline{r}_c$ *(UTS)*

Charge	3112	3113	3114	3116	3117	3120	*(UTS)*
$r_{c,CF\text{-}CR}$ *(UTS)*	0.98	0.99	0.86	0.82	0.92	1	0.94
$r_{c,HF\text{-}HR}$ *(UTS)*	0.88	0.99	0.88	0.86	0.97	0.67	0.84

Previous studies [20, 24, 25] on the same six (6) charges indicated that applied homogenization process resulted in an increase of the number of grains per unit area $\overline{N}_{A,H} = 75.85$ No./mm^2 compared to the as-cast state $\overline{N}_{A,C} = 64.53$ No./mm^2, but with equal grain distribution within each section, i.e. the number of grains increases from the ingot centre toward its edges. The aforementioned variation of the number of grains over the ingot cross-section is influenced by the casting i.e. solidification process, and thus the differences caused by the intensity of heat withdrawal and the formation of structural zones in the ingot. Although the melt inoculation suppresses formation of trancrystalline columnar grain zone, it is not possible to obtain equiaxed crystals of approximately equal size within the whole ingot section. Decrease of the mean coefficient variation for the number of grains per unit area for the homogenized ingots' fronts and rears for all investigated charges was determined and compared to those in as-cast state. Also, the total mean coefficients of variation decrease from $\bar{V}_{,CNA} = 31.41$ % to $\bar{V}_{,HNA} = 27.80$ % was noticed, indicating a more uniform distribution of grain size per unit area after heat treatment [26].

Given the total coefficient of correlation for the number of grains for all charges $\overline{r}_{š,HF\text{-}HR}(N_A) = 0{,}81$ between the homogenized ingots' fronts and rears, it is apparent that applied casting technology and melt treatment as well as homogenization methodology (time and temperature parameters) provides satisfying microstructural homogeneity of the ingots as a whole. Additional investigations [27] confirmed that the homogenization duration does not affect the change in the number of grains per unit area. The number of grains per unit area depends only from the casting local cooling rates defined with the position within the ingot and/or slice (*i, j*).

2.2. Influence of individual variables on elongation

Figure 5 is graphic representation of the relationship between the individual variables (charge, slice height/ingot depth and slice width/ingot width) and *the mean elongation in as-cast state* in EN AW-5083 specimens.

Graphic representation of the relationship between individual variables and mean elongation A_{50} in as-cast state for the:

a) ingot front section

- The effect of the *charge* shows significant variations of elongation in both directions in relation to the total arithmetic mean for the ingot front section ($\overline{A_{50,FC}}$ = 18.06 %);
- The influence of the *slice height (i)* shows deviation of elongation from total arithmetic mean as a very pronounced increase from -1.97222 % for i = 1 (ingot centre) with standard deviation of 4.443160 to +3.7778 % for i = 6 (ingot edge) with standard deviation 3.011091;
- The influence of the *slice width (j)* indicates deviation of elongation from total arithmetic mean with the parabolic trend of elongation with minimum of -1.05556 % with standard deviation of 5.403702 positioned in edge-inner level of the slice (j = 5) and maximum at the edge level of the slice +1.44444 % (j = 1) with standard deviation of 2.683282.

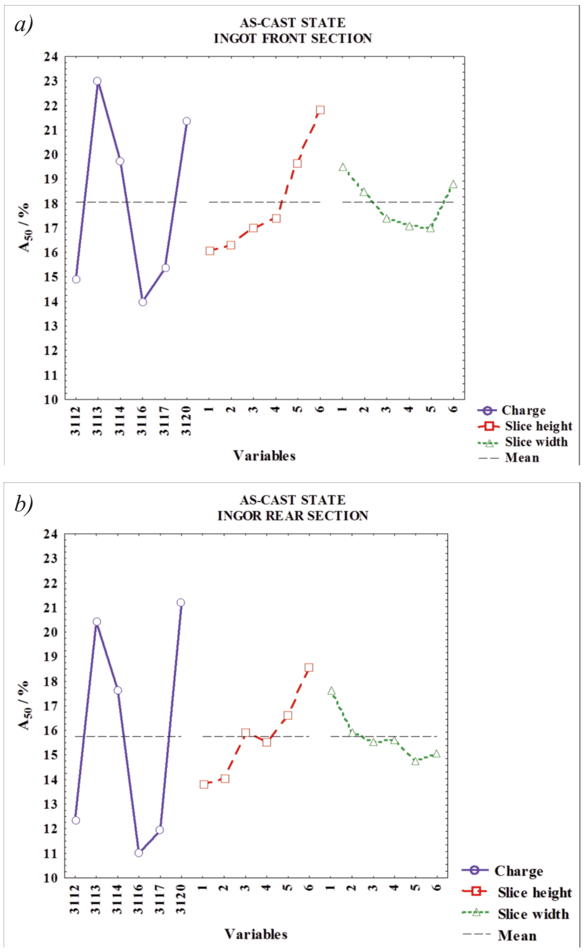


Figure 5. *Graphic representation of the relationship between individual variables and elongation (as-cast state) a) ingot front section; b) ingot rear section*

b) ingot rear section

- The effect of the *charge* shows significant variations of elongation in both directions in relation to the total arithmetic mean for the ingot rear section ($\overline{A_{50,RH}}$ = 15.75 %);
- The influence of the *slice height (i)* shows deviation of elongation from total arithmetic mean as a very pronounced increase from -1.91667 % for the level i = 1 (ingot centre) with standard deviation of 4.479583 to +2.83333 % for the level i = 6 (ingot edge) with standard deviation of 4.247548. Elongation representation follows the trends of ultimate tensile strength and number of grains per unit area behaviour.
- The influence of the *slice width (j)* indicates deviation of elongation from total arithmetic mean with the decreasing trend with minimum of -1.00000 % with standard deviation of 6.524952 positioned in edge-inner level of the slice (j = 5) and maximum at the first edge level of the slice +1.91667 % (j = 1) with standard deviation of 3.710346.

Table 6 reveals the variation analysis for elongation A_{50} for the ingots' fronts and rears, with remarkable significance of differences for all three variability sources (P < 0.5).

Figure 6 is graphic representation of the relationship between the individual variables (charge, slice height/ingot depth and slice width/ingot width) and *the mean elongation in homogenized state* in EN AW-5083 specimens.

Graphic representation of the relationship between individual variables and mean elongation A_{50} in homogenized state for the:

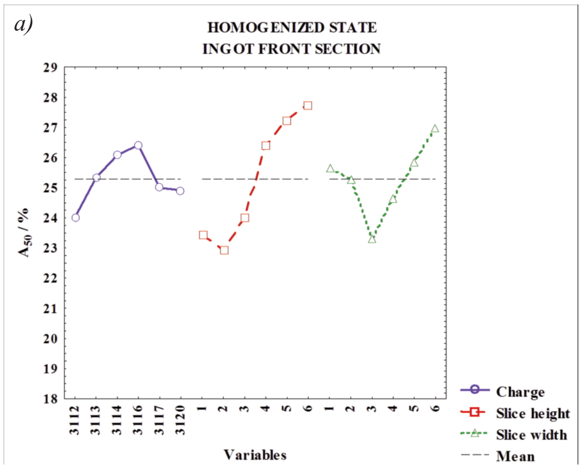
a) ingot front section

- The effect of the *charge* do not shows significant variations of elongation in both directions in relation to the total arithmetic mean ($\overline{A_{50,PH}}$ = 25.29 %);

Table 6. *Analysis of variance of the Latin square for the elongation - ingots' front and rear sections - as-cast state*

Variables	Sum of Squares		Degrees of Freedom		Mean Squares		*F*-Test		Significance *P*	
	F	R	F	R	F	R	F	R	F	R
Charge	*430.6389*	*622.3333*	*5*	*5*	*86.12778*	*124.4667*	*225.4982*	*64.79826*	*0*	*0*
Slice height	*151.4722*	*91.5833*	*5*	*5*	*30.29445*	*18.3167*	*79.3164*	*9.53579*	*0*	*9e-005*
Slice width	*32.1389*	*31.4167*	*5*	*5*	*6.42778*	*6.2833*	*16.8291*	*3.27115*	*1e-006*	*0.025529*
Residual	7.6389	38.4167	20	20	0.38194	1.9208				

- The influence of the *slice height (i)* shows deviation of elongation from total arithmetic mean as a very pronounced increase from – 1.87500 % for $i = 1$ (ingot centre) with standard deviation of 3.441172 to + 2.45833 % for $i = 6$ (ingot edge) with standard deviation 1.440486;
- The influence of the *slice width (j)* indicates deviation of elongation from total arithmetic mean with the parabolic trend with minimum of - 1.95833 % with standard deviation of 2.732520 positioned in inner level of the charge ($j = 3$) and maximum at the edge levels of the charge + 1.70833 % ($j = 6$) with standard deviation of 1.643168.



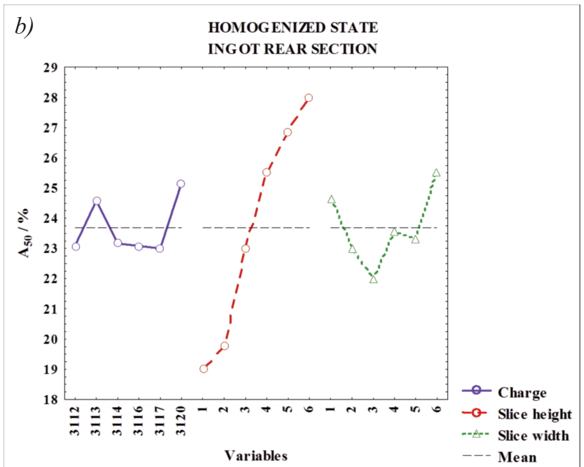


Figure 6. *Graphic representation of the relationship between individual variables and elongation (homogenized state) a) ingot front section; b) ingot rear section*

b) ingot rear section

- The effect of the *charge* shows significant variations of elongation in both directions in relation to the total arithmetic mean for the ingot rear section ($\overline{A_{50}}_{,KH} = 23.68$ %);
- The influence of the *slice height (i)* shows deviation of elongation from total arithmetic mean as a very pronounced increase from -4.68056 % for the level $i = 1$ (ingot centre) with standard deviation of 2.469818 to +4.31945 % for the level $i = 6$ (ingot edge) with standard deviation of 1.816590. Elongation representation follows the trends of ultimate tensile strength and number of grains per unit area behaviour.
- The influence of the *slice width (j)* indicates deviation of elongation from total arithmetic mean with the decreasing trend with minimum of - 1.68056 % with standard deviation of 4.460942 positioned in inner level of the charge ($j = 3$) and maximum at the edge level of the charge + 1.81944 % ($j = 6$) with standard deviation of 4.690416. Elongation representation also follows the trends of ultimate tensile strength and number of grains per unit area behaviour.

Variation analysis for elongation A_{50} of the homogenized ingots front, shown in Table 7, reveals significant difference in the *slice height and width*, while the *charge* as a source variability did not show significant influence based on significance P ($P = 0.163496$). Variation analysis for elongation A_{50} of the homogenized ingots' rears, shown in Table 7, shows significant difference significance only for *slice height* based on significance P ($P = 0.000000$). The third source of variability of the *slice width* is slightly significant, indicating the likelihood of the first type of error, $P = 0.063020$. The *charge* source variability is not significant.

Applied homogenization procedure in semi-industrial conditions, a significant increase in elongation for all the examined samples, and thus the total mean value from $\overline{A_{50}}_{,C} = 16.91$ % for the as-cast state to $\overline{A_{50}}_{,H} = 24.49$ % for the homogenized state was observed. Also, relatively high mean coefficient of variation for ingots' fronts for all investigated charges is $\overline{V}_{,A50\text{-}FH} = 10.69$ %, which is for 3.65 % lower than

Table 7. *Analysis of variance of the Latin square for the elongation - ingots' front and rear sections - homogenized state*

Variables	Sum of Squares		Degrees of Freedom		Mean Squares		*F*-Test		Significance *P*	
	F	R	F	R	F	R	F	R	F	R
Charge	22.7292	26.7847	5	5	4.54583	5.35694	1.77687	1.4632	0.163496	0.245743
Slice height	*131.8125*	*418.368*	*5*	*5*	*26.3625*	*83.67361*	*10.30456*	*22.8547*	*5.3e-005*	*0*
Slice width	*45.4792*	46.2014	*5*	5	*9.09583*	9.24028	*3.55538*	2.5239	*0.018382*	0.06302
Residual	51.1667	73.2222	20	20	2.55833	3.66111				

those for as-cast state [20]. The increased mean coefficient of variation for the homogenized ingots' rears for all examined charges $\bar{V}'_{A50-RH}$ = 17.33 %, which is for 1.51 % higher than those for as-cast state, indicates a somewhat unequal distribution of elongation when compared to those at ingots' fronts. However, comparison of the total mean coefficient of elongation variation for the homogenized state $\bar{V}'_{A50-H}$ = 14.01 % which is slightly lower than those in as-cast state $\bar{V}'_{A50-L}$ = 15.08 % which indicates lower total results dissipation.

The total correlation coefficient for elongation $\bar{r}_c(A_{50})$ = 0.65 between the ingots' fronts and rears of particular ingot i.e. charge, shown in Table 8, indicates that the homogeneity of homogenized ingots from the elongation aspect is achieved, although significantly reduced when compared to as-cast state.

Table 8. *Correlation coefficient for elongation of investigated charge samples in as-cast $r_{c,CF-CR}(A_{50})$ and homogenized state $r_{c,HF-HR}(A_{50})$ and total correlation coefficient $\bar{r}_c(A_{50})$*

Charge	3112	3113	3114	3116	3117	3120	$\bar{r}_c(A_{50})$
$r_{c,CF-CR}(A_{50})$	0.57	0.59	0.83	0.92	0.96	0.71	0.92
$r_{c,HF-HR}(A_{50})$	0.87	0.87	0.33	0.37	0.91	0.74	0.65

Summarizing the results of the elongation influenced variables, it can be noticed that all observed variables (charge, slice height and width) have a high influence. The charge variation is caused by the change in chemistry and casting parameters and related microstructural and ultimate tensile strength variations. The elongation variation with the slice height or width change reflects to the change in the microstructure expressed with the number of grains per unit area variations, respectively. Both ultimate tensile strength and elongation follow this change of microstructure, i.e. theirs increase with an increase of the number of grains per unit area have been noticed.

4. Conclusions

Homogeneity of EN AW-5083 alloy in as-cast and homogenized state was investigated using statistical analysis. An overview of solidification and homogenization processes influence was obtained on the base of mechanical properties investigation performed at six (6) EN AW-5083 alloy ingots' fronts and rears in as-cast and homogenized state. Obtained mechanical properties were also correlated to number of grains per unit area. Quantification and statistical processing of obtained results enabled determination of following conclusions:

Homogenization process influences on significant increase of ultimate tensile strength and elongation for both ingots' fronts and rears and for all charge samples.

Analysis of the influenced variables indicates the ultimate tensile strength and elongation changes within the particular charge and per slice height and width following the microstructure development, i.e. linear correlation of number of grains per unit area both in as-cast and homogenized state;

High total correlation coefficient for ultimate tensile strength and elongation indicates a high degree of correlation between the ingots fronts and rears, i.e. to overall homogeneity within all homogenized ingots.

High homogeneity is a result of effective melt treatment (AlTiB), as well as controlled casting parameters, solidification process and cooling of ingots. Homogenization methodology (time and temperature regime) provides satisfactory structural homogeneity of the ingots as a whole.

The results of this investigation provide new insights into the quantification of the significant variables influence, dependent from local cooling parameters defined by the position in the charge (*i, j*) and number of grains per unit area followed by mechanical properties development. Selection of sampling position with respect to charge, slice height and width followed by correlation with obtained trends enables estimation of ingot quality in both as-cast and homogenized state.

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