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Research Article

Experimental Study of Correlation of Mechanical Properties of Al-Si Casts Produced by Pressure Die Casting with Si/Fe/Mn Content and Their Mutual Mass Relations

Marcel Fedak, Miroslav Rimar, Ivan Corny, and Stefan Kuna

Faculty of Manufacturing Technologies with Seat in Prešov, Department of Process Technology, Sturova 31, 080 01 Prešov, Slovakia

Correspondence should be addressed to Marcel Fedak; marcel.fedak@tuke.sk

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The submitted contribution addresses problems concerning influence of alloying elements (Si/Fe/Mn) of Al-Si pressure die casts (HPDC) on values of residual deformation. On the basis of results of executed experiments, mutual correlations are analyzed and described, while not only measurements results are evaluated but also metallographic outputs of obtained compounds from the view of their formation, occurrence, and size. The development of intermetallic phases structures Al(FeMn)Si as well as intermetallic ferritic phase Al_3FeSi was observed. More verification experiments follow in order to apply obtained knowledge for improvement and/or preservation of casts properties on required level.

1. Introduction

Parts manufactured by pressure die casting distinguish by suitable properties in relation to their mass. In present, these products/casts are utilized in various spheres of industries, significant share of which is automotive industry [1]. An important requirement in this sphere is resultant mass of products, whilst all claimed properties are preserved. The trend of mass reduction leads to application of aluminium-based materials, while demands on strength, extensibility, and other mechanical properties are on the same level as for Fe-based materials.

The paper describes basic impacts of chosen alloying elements on permanent deformation as a significant mechanical property. Mutual correlations between chosen alloying metals and resulting deformation measured on a group of casts are described. Consecutively these relations are observed during variation of content of the alloying elements in order to increase resulting strength of the cast. Providing stability in casting process is of great importance, since it has direct impact on resulting cast properties [2–4]. Aluminium alloys are die cast under pressure on casting machines with cold chamber [5, 6]. Significant factor of the process is corrosive effect of liquid aluminium alloys particularly at higher temperatures, this effect makes it impossible to employ casting machines with hot chamber [6–8]. Horizontal cold chambers are relatively simple, and it is possible to apply higher specific pressure on the cast metal. Thus, it is possible to cast light-walled casts with smooth surface and high mechanical properties. These advantages of horizontal chamber make it possible to design large casting machines with voluminous loading chamber and closing force F_u up to 30 MN, with gross cast mass 30 kg or more, in casting of aluminium alloys (charge utilization of 80%) [6, 9, 10].

The quality of aluminium casts produced by pressure die casting depends closely on the content of alloying elements [5, 6, 11–15]. The properties of chosen alloying elements are described in Table 1.

Concentration of alloying elements in the cast is chosen according to requirements on the cast properties; however, the concentrations are limited by recommended ranges [11].

Iron and silicium are very often contained in aluminium alloys. Both of these elements influence mechanical properties of the casts. Theoretical knowledge shows that iron

Table 1: Characteristic, properties, and impact of chosen alloying elements [11, 12, 14–20].

Element	Characteristic
B	Content refines structure and increases electrical conductivity in technically clean aluminium due to precipitation of V, Cr, Mo, and Ti from solid solution
Bi	Alloying with this element improves mechanical machinability
Sb	It serves for improving of corrosion resistance in salty water solutions; in Al-Mg compositions decreases tendency to crack generation
Cr	Alloying with this element decreases susceptibility of grain growth in Al-Mg alloys; in hardenable alloys it increases hardening capacity
Cu	It decreases solidification shrinkage and enables thermal hardening; undesirable effect is a decrease in corrosion resistance; most often it is used along with Mg
Co	In some Al-Si alloys with Fe present, it is added to transform needle-shape β phase rich in iron into sphere morphology; this improves strength and plastic properties
Fe	In Al-Si alloys, it occurs as an impurity; solubility in solid state is low (approx. 0.04%); due to this, it is present in structure as intermetallic compound with aluminium Al_5FeSi; in Al-Cu alloys it creates intermetallic compound Al_7FeCu_2, thus reducing copper content in solid solution α which leads to a decrease of strength properties
Mg	It is alloyed in order to increase strength properties by hardening formation of intermetallic compound Mg_2Si; it deteriorates fluidity and improves machinability
Mn	It is alloyed into aluminium alloys in order to improve strength, to increase recrystallization temperature, to refine grains, to block grain growth in the case of its segregation in form of disperse precipitates, and to suppress iron segregation in lamellar form; for elimination of harmful iron influence, it is usually added in half content of the iron content
Mo	It is alloyed up to 0.3% in order to refine structure
Ni	It is alloyed in order to improve strength of Al-Cu, Al-Si alloys at higher temperatures; it improves corrosion resistance
Si	In Al-Si alloys, it is the main alloying element, presence of which improves casting properties; comparing with properties of pure aluminium, depending of silicium content, strength is increased
Ti	It is alloyed together with B in order to refine structure

content higher than 1–1.4% has negative impact on the cast properties [5, 6, 11].

2. Materials and Methods

2.1. Preparation of Experimental Casts. Casting machine CLH 400.01 was applied for the experimental casting. It is horizontal pressure machine with cold chamber, with manual dosing of metal. Other operations of casting process run in semiautomatic cycle, so that all conditions of casting cycle could be replicated. In semiautomatic regime of the machine with horizontal cold chamber, an operator manually scoops up metal with the scoop from the heating furnace and pours it into loading chamber. All other operations including ejection of the cast from the mould are automatic with electrohydraulic safety system for particular operations.

Set of 80 specimens were cast at a given technological order (Table 2). Every eighth cast specimen were selected for experimental evaluation, so that the whole range of usable capacity of the heating furnace would be represented.

Table 2: Technological order and casting parameters.

Basic pressure	30 ± 2 MPa
Path of third velocity	270 mm
Third velocity	2.5 rev.
Chamber diameter	60 mm
Size of pellet	25 mm
Temperature of meltage	660 ± 20°C
Insert under the chamber	40 mm
Dose mass into chamber	1300 g
Dosing scoop number	5
Cycle time	50.42 s
Solidification time	4 s
Pressing time	5 s
Unload discharge time	2 s

2.2. Evaluation Method by Pressure Tests of Residual Deformation. This is a type of pressure test which follows residual deformation; the term residual deformation means deformation measured at partial unload discharge. The load is evoked by force F_{E1}. When maximal value of deformation evoked by this force is reached, the value of the force is decreased to value F_{E2}. Time of force F_{E2} effect is usually 10 s.

It holds true that

$$F_{E2} = \frac{1}{2} F_{E1}. \quad (1)$$

Residual deformation tests were carried out on device TIRA test 28200. Initial load force was set on value F_{E1} = 86 kN with loading speed 10 mm s^{-1}. When maximum

Table 3: Intervals of contents of particular elements as stated by the norm STN EN 42 4331.

	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Zn (%)	Ni (%)	Cr (%)	Pb (%)	Sn (%)	Ti (%)	V (%)	Al (%)
Min.	8.00	0.60	2.00	—	0.05	—	—	—	—	—	—	—	—
Max.	11.00	1.10	4.00	0.55	0.55	1.20	0.55	0.03	0.35	0.25	0.25	—	—

Table 4: Values of chemical compositions of particular cast samples and values of residual deformation.

Sample	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Zn (%)	Ni (%)	Cr (%)	Pb (%)	Sn (%)	Ti (%)	V (%)	Al (%)	Def. (mm)
A1	9.87	0.91	2.27	0.28	0.14	0.74	0.06	0.03	0.12	0.04	0.03	0.01	85.50	0.293
B1	9.88	0.89	2.31	0.27	0.13	0.76	0.06	0.03	0.12	0.04	0.03	0.01	85.48	0.290
A2	9.72	0.87	2.24	0.26	0.14	0.74	0.06	0.03	0.12	0.04	0.03	0.01	85.74	0.296
B2	9.76	0.88	2.22	0.27	0.13	0.74	0.06	0.03	0.12	0.04	0.03	0.01	85.71	0.292
A3	9.72	0.87	2.29	0.26	0.13	0.76	0.06	0.03	0.12	0.04	0.03	0.01	85.68	0.295
B3	9.51	0.86	2.2	0.27	0.12	0.74	0.06	0.03	0.11	0.04	0.03	0.01	85.99	0.291
A4	9.49	0.87	2.24	0.27	0.13	0.75	0.06	0.03	0.12	0.05	0.03	0.01	85.95	0.316
B4	9.39	0.85	2.21	0.25	0.13	0.73	0.06	0.03	0.12	0.04	0.03	0.01	86.14	0.313
A5	9.41	0.83	2.24	0.25	0.13	0.74	0.06	0.03	0.12	0.05	0.03	0.01	86.08	0.312
B5	9.48	0.85	2.24	0.25	0.13	0.74	0.06	0.03	0.12	0.05	0.03	0.01	86.00	0.311
A6	9.3	0.82	2.19	0.25	0.14	0.76	0.06	0.03	0.12	0.05	0.03	0.01	86.20	0.327
B6	9.47	0.85	2.21	0.25	0.14	0.76	0.06	0.03	0.12	0.05	0.03	0.01	86.02	0.305
A7	9.49	0.85	2.22	0.24	0.13	0.75	0.06	0.03	0.12	0.04	0.03	0.01	86.03	0.316
B7	9.41	0.83	2.16	0.25	0.13	0.75	0.06	0.03	0.11	0.04	0.03	0.01	86.19	0.306
A8	9.32	0.81	2.25	0.22	0.13	0.75	0.06	0.02	0.12	0.05	0.03	0.01	86.23	0.334
B8	9.28	0.83	2.24	0.23	0.13	0.75	0.06	0.02	0.12	0.05	0.03	0.01	86.25	0.338
A9	9.34	0.81	2.28	0.22	0.13	0.75	0.06	0.02	0.12	0.05	0.02	0.01	86.19	0.331
B9	9.23	0.79	2.21	0.23	0.13	0.76	0.06	0.02	0.12	0.05	0.03	0.01	86.36	0.336
A10	9.44	0.81	2.25	0.23	0.13	0.75	0.06	0.03	0.12	0.05	0.03	0.01	86.09	0.33
B10	9.32	0.8	2.24	0.22	0.13	0.73	0.06	0.03	0.12	0.04	0.04	0.01	86.26	0.323

deformation value was reached, the load was decreased to the value $F_{E2} = 43\,\text{kN}$, at which the residual deformation was observed during 10 s. Measurements were carried out on ten specimens, courses were recorded and processed by system TIRA test. Ambient temperature during tests was kept at $23 \pm 0.5^{\circ}$C.

2.3. Observing Chemical Composition of the Casts. Analysis of chemical composition was observed on spectrophotometer SPECTROLAB JR.CCD 2000. Measurements provided chemical compositions of the casts in the place of openings (A, B). The samples were detached in such a way that no thermal impacts have occurred. Surfaces were adjusted by milling technology. Shape of the samples was formed to achieve square plane with a side of 20 mm. Three measurements for every sample were carried out according to procedure for chemical composition measurements by spark erosion.

The analysis of the casts provides mass content percentage of the following elements: Si, Fe, Cu, Mn, Mg, Zn, Ni, Cr, Pb, Sn, Ti, Na, Sr, V, Zr, and Al. Table 3 shows values of boundary intervals of contents for particular elements according to the norm STN EN 42 4331.

3. Results

3.1. Chemical Composition. The results of chemical composition measurements have shown decrease in the content of observed elements in casting process. Particular casts indicate variations of the contents with decreasing tendency. The results directly correspond to the results of observation of content changes in heating furnace that are described in contributions dealing with casting process variations [21, 22]. The results are given in Table 4.

From measurements of the chemical composition of each sample (Table 4), the track of changes to the content of the particular elements, depending on the time, can be kept. These changes are directly reflected in the element content of castings, and interval of the change is 7.04% for Si, 15.19% for Fe, and 27.27% for Mn.

On the basis of the analysis, it was suggested to stabilize or slightly increase iron content and to directly increase manganese content. An iron content should be up to one percent because—as it is given in the theory and also prescribed by the norm—exceeding of iron content above 1.4% causes strong negative effects [6, 11]. Relation of iron and manganese content was determined on the basis of measurements to 3.15 : 1. According to this relation and to

Table 5: Obtained content values of chosen elements (Si/Fe/Mn) of particular samples of the casts and values of residual deformation after content correction of Fe-Mn.

Sample	Si (%)	Fe (%)	Mn (%)	Def. (mm)
A11	9.5	0.95	0.35	0.284
B11	9.58	0.98	0.35	0.282
A12	9.26	0.94	0.35	0.287
B12	9.46	0.96	0.34	0.284
A13	9.22	0.91	0.3	0.29
B13	9.34	0.94	0.34	0.29
A14	9.18	0.94	0.32	0.293
B14	9.3	0.93	0.32	0.293
A15	9.07	0.91	0.31	0.294
B15	9.24	0.91	0.31	0.296
A16	9.06	0.87	0.3	0.296
B16	9.17	0.86	0.3	0.298

cast manufacturer requirements, also taking into account possibilities to change alloy composition, the iron content for further experimental evaluation was set on value 0.90 to 0.95% Fe, and the manganese content was set 0.35% to 0.38% Mn.

The experiment that followed was based on suggested iron and manganese content values. The set of casts was produced with the same methodology as in previous case. Six casts from the set were selected for residual deformation and chemical composition analyses. Obtained values are shown in Table 5.

Dependence courses of particular casts on chemical composition on casting order of the casts are given in Figure 1.

3.2. Residual Deformation. In this part, dependence courses of residual deformation on chemical composition of the casts are observed. Particular influences of chosen alloying elements are given in introductory part of the paper. An influence of iron and manganese on resulting residual deformation was observed, at the same time, a possible influence of silicium content variation was evaluated. Considering that Si influences fluidity, all observed casts were X-ray tested, and no internal defects were detected. Also, visual and dimensional inspections did not show any negative changes of the casts. Figure 2 gives dependence courses of residual deformation on chosen elements content.

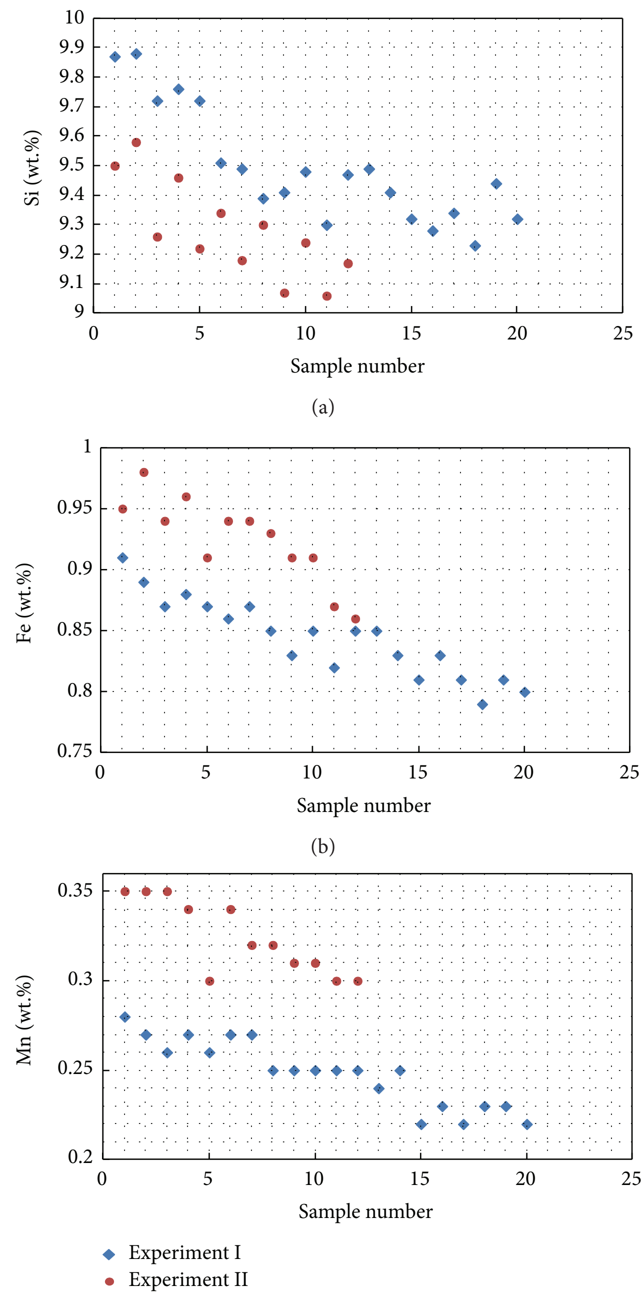

Figure 1: Values of chemical composition (Si/Fe/Mn) for the experiments.

4. Discussion

4.1. Influence of Iron and Manganese Contents on Values of Residual Deformation. For increasing values of iron content, it is possible to see the decrease of residual deformation values (Figure 2, Fe (wt.), exp. I). The decrease is also observed at the manganese content increase (Figure 2, Mn (wt.), exp. I). In proposal for iron content in aluminium alloy, the content intervals were suggested, and these intervals were not exceeded during analyses. In one case, the iron content value (0.98%) exceeded recommended range (0.90 to 0.95% Fe); however, no negative effect was observed.

Figure 2 shows diagrams representing whole range of observed iron and manganese contents and residual deformations which depend on those contents. From the diagrams, the decrease in residual deformations in dependence on alloying elements increase is apparent. The recorded decrease for residual deformation was 19.85% for the observed samples. The coupling of the iron content and manganese content can be observed also; this is represented by residual deformation. The test of functional dependences was carried out. At first, the correlations between iron and manganese contents

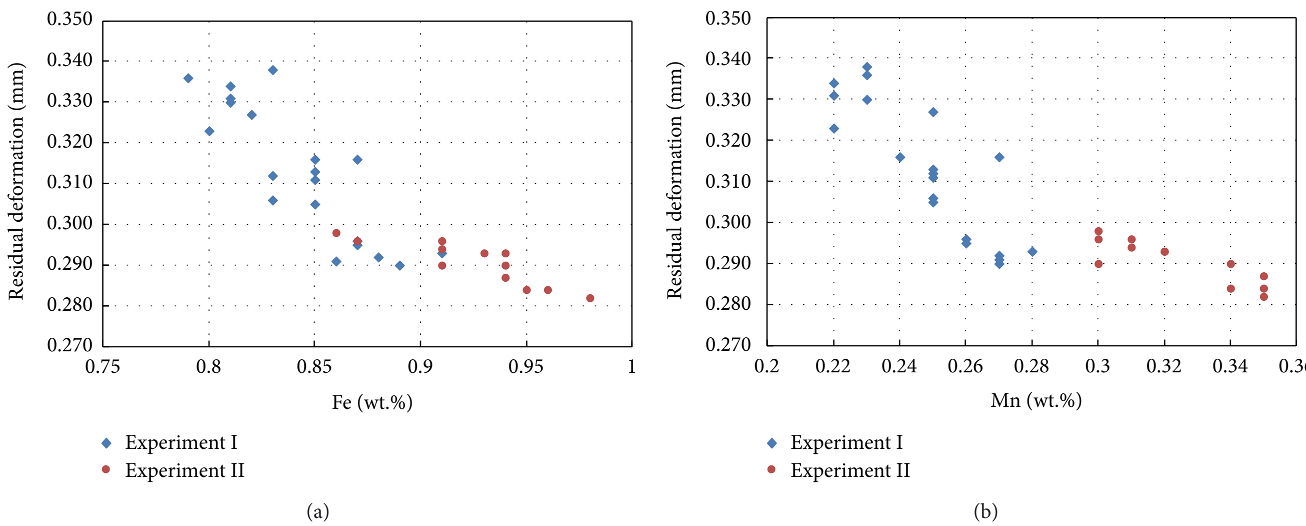

Figure 2: Dependence courses of residual deformation on change of Fe and Mn content.

in aluminium alloy and residual deformation were observed independently. In the following, the complex dependences between the parameters were described. For analyzed places A and B, the value of correlation coefficient for measuring of iron content and residual deformation was determined on −0.868, and for manganese content and residual deformation, it was determined on −0.838. The mutual correlation between iron and manganese content was determined on 0.944. Values of correlation coefficients indicate indirect functional dependences between iron content, manganese content, and residual deformation. Values approach significantly the value −1, so the high degree of the correlation can be noted. Multiple coefficient of correlation for analyses in places A and B has value 0.0954. Cummulative characteristic of residual deformation dependence on Mn and Fe content is shown in Figure 3. Differences between measured-out points and theoretical area fall within supposed range, whilst mutual relations of Mn and Fe changes can be observed. The behaviour can be explained from metallurgy point of view by formation of structures on the Al-Fe-Mn-Si basis and their variations, with an assumption that structures with lesser content of alloying elements contain more massive formations of intermetallic phases Al(FeMn)Si and lower content of Mn causes more frequent occurrence of intermetallic ferritic phase Al_3FeSi [11]. This was the reason to carry out analysis to evaluate the samples. Therefore, the metallographic analysis was carried out to evaluate the particular samples in terms of the formation of structures as well as their possible effect on the mechanical properties of the casts.

From the analysis of microscopic images, it follows that structures of A1, A2, B1, and B2 samples (Figure 4) contain fine structural zones of intermetallic phases Al(FeMn)Si and defects in the form of bubbles in dimensional range $\langle 8; 11 \rangle\ \mu$m. Structures of A8, A9, B8, and B9 (Figure 4), on the other side, contain more massive structural zones of intermetallic phases Al(FeMn)Si and internal defects in greater dimensional interval $\langle 10; 30 \rangle\ \mu$m. Also the structures

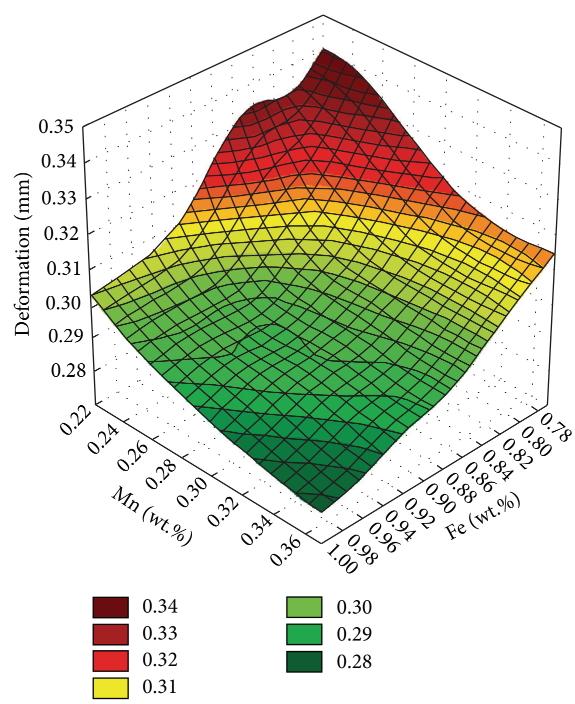

Figure 3: Dependence of permanent deformation on iron and manganese.

of ferritic phase Al_3FeSi and intermetallic phase $FeSiAl_5$ are observed as more massive needles. In the case of $FeSiAl_5$, long needles are forming; these can cause defects due to the notch effect. Variations of ferritic phase Al_3FeSi from massive and more frequent in samples A8, A9, B8, and B9 to finer and less frequent in samples A1, A2, B1, and B2 correspond to the increase in Mn content. All images also show particles of undissolved silicium in a form of irregular objects.

More massive structural zones of ferritic phase Al_3FeSi have negative effects on values of residual deformation,

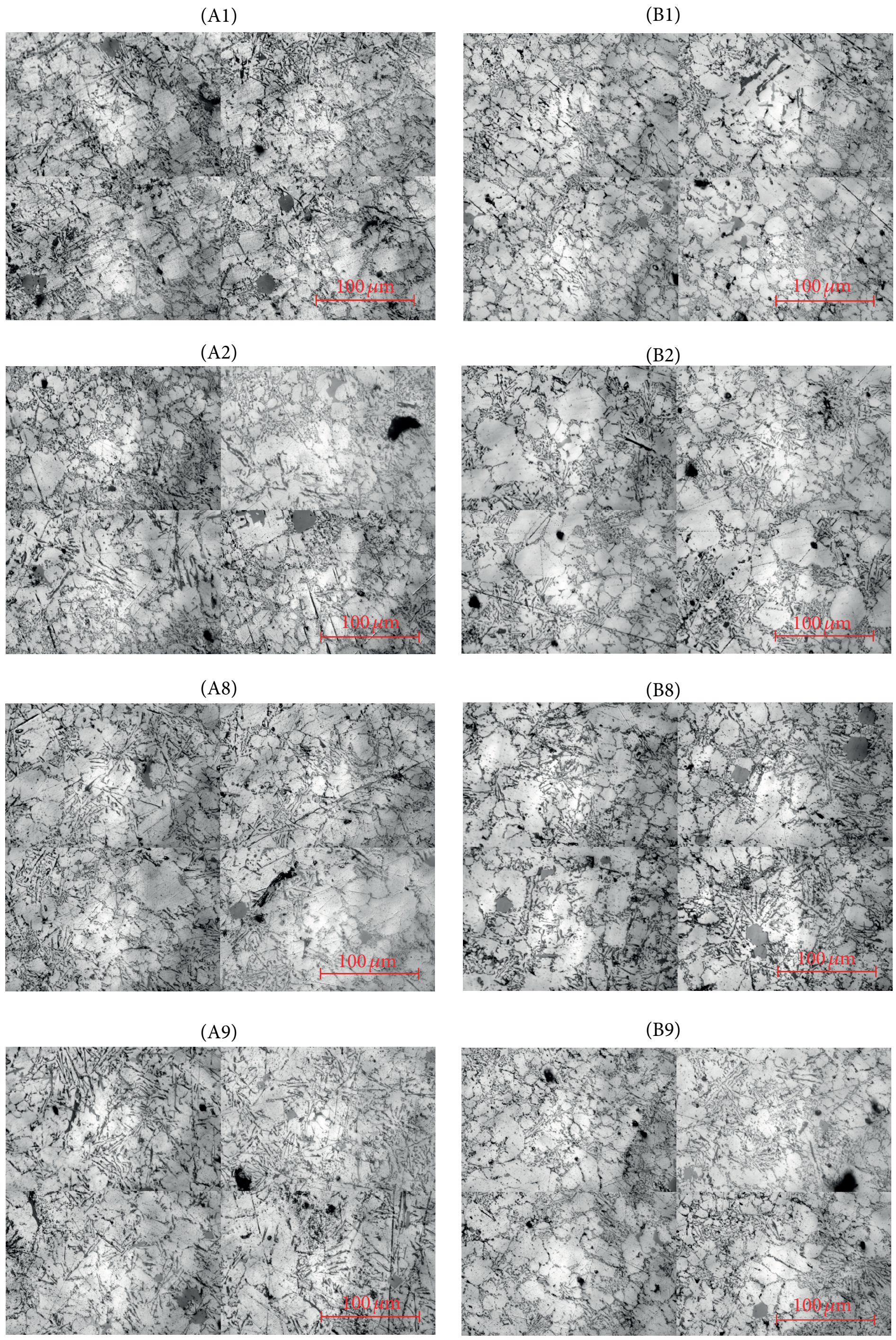

Figure 4: Metallographic images of boundary casts.

while they are compensated by increasing manganese content which causes refining of Al_3FeSi phase and formation of intermetallic Al(FeMn)Si phases. These structures are more beneficial in terms of exposure to residual deformation.

In the case of manganese, it is necessary to observe the correlation, because if it is not saturated, and it is eventually deposited as a thermal compound AlMnSi.

5. Conclusions

Realized experiments and discussions show several important aspects of obtained and verified knowledge. Experiments were focused on a group of three elements (Si, Fe, and Mn) occurring in subeutectic Al-Si alloy. Selection of the group was based on knowledge of realized measurements obtained within monitoring of processes in heating furnaces, where variations of elements concentration have been observed. The variations relate to silicium, iron, and manganese, all in decreasing trends.

Described results also show that in casting process, concentration variation of silicium, iron, and manganese may occur, whilst these variations in the conditions of real experiment have reached values for Fe 15%, for Mn 27%, and for Si 7%. Also, an influence of these variations on values of residual deformation was confirmed; theoretical approach was proved. The change of deformation in such a case is 16% from observed interval. At the same time, it is possible to evaluate correlation coupling of Si/Fe/Mn with regard to the metallographic tests results.

From verification measurements and from overall behaviour of particular ingredients, it can be concluded that even though the iron is an impurity, it can be used to increase compression strength for loads in incomplete unload discharge. The mean deformation value of standard meltage presents value 0.313 mm with standard deviation 0.0163 and variance of residual deformation $2.69E-4$. Repeated tests with increased values of Fe and Mn contents showed decrease in mean deformation value to 0.2905 mm with standard deviation 0.0053 and variance of residual deformation $2.826E-5$. Results demonstrated decrease in deformation on an average 7.6%. In such a case, it is suitable to apply interval of Fe content up to 0.95% of mass content. However, it is vital to proportionally increase amount of manganese too, in order to refine structures. If the growth of needle-shape structures is significant, there is a chance of local defects in form of slipping planes; that is, why refined structures are sought for.

Taking into account the variations of alloy content comparing to commercial alloys, it is possible to ensure alloying elements content increase during melting process by subsidizing the particular ingredients or by proper combination of recurrent material.

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