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Influence of die and casting temperatures and titanium and strontium contents on the technological properties of die-cast A356 in the as-cast and T6 condition

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Abstract

Automobile manufacturers demand downsized components manufactured from materials possessing increased technological properties. To fulfill this, the processing of existing materials must be optimized. In the present study, the individual effects and interactions of the melt's treatment and process parameters on the mechanical and metallographic properties were investigated in the as-cast and T6-states. This was carried out with the help of the Taguchi method to optimize the technological properties of this much used die-cast A356 alloy. The interaction effects of the parameters considered in this study are hardly addressed in the literature. However, the results of the present investigation show that this aspect is fundamental for optimizing the technical properties of a die-cast A356 alloy. For example, the titanium content of 0.20 wt.%, conventionally used for grain refinement, can be reduced by up to 75 % when the die temperature is relatively low (here: 190 °C). This leads to increased as-cast technological properties and cost savings.

Introduction

In times of increased energy prices and stricter environment laws, downsizing of castings is one key to reduce the fuel consumption and to decrease the emission of automobiles [1-3]. Downsizing of castings represented by lower wall thicknesses demands a casting material with increased technological properties to withstand the service loads. Besides adapting the chemical composition, this objective can be achieved by optimizing the casting material's processing [4].
Aluminum alloys are gaining popularity in the field of automobile manufacturing since these materials combine a relatively low density with good casting and mechanical properties, e. g. A356 alloy [5-9]. The processing of A356 includes, besides the typical degassing procedure, the addition of a grain refining agent. This agent mainly contains titanium to decrease the size of the primary aluminum solid solution, and the eutectic silicon is modified by adding strontium. Both process steps have a large influence on the casting and the mechanical properties of aluminum-silicon casting alloys; which has already been investigated in numerous studies [7-18]. Owing to the introduction of the grain refining agent and the associated change of the solidification morphology from exogenous to endogenous solidification, the melt's flowability, mold filling and feeding ability is increased, and the tensile strength and ductility of the casting is also improved due to an increased number of grain boundaries and smaller grains [13, 14]. Usually, to achieve the best grain refinement of A356, alloy producers and the literature suggest titanium contents of 0.20 wt.% [15, 16]. The modification with strontium (usually 200 ppm) causes a smaller, compact and fibrous eutectic silicon phase which leads to improved tensile strength and ductility of A356 castings [17, 18]. Besides these melt treatments, the casting process parameters also exhibit an influence on the microstructure and the technological properties of A356. To process A356, a casting temperature of 700 °C to 720 °C seems to be ideal since this temperature supports the feeding of the melt and the stability of nuclei [19]. The die temperature should be high enough to ensure complete filling of the cavity and should also be low enough for an increased cooling rate. The latter causes a lower dendrite arm spacing (DAS) and grain size leading to increased mechanical properties [20-23]. Mostly however, the single effects of the particular processing steps on the mechanical properties of A356 are investigated and therefore only limited statements exist about the interaction and the intensity of the effect of these parameters. To optimize A356's technological properties, the influence of the interaction of its processing parameters is vitally important.
In the present study, the die and casting temperatures, and the titanium and strontium contents were varied according to an orthogonal L18-Taguchi array to show their single and interaction influences on the mechanical properties of an A356 in the as-cast and T6 states. These results allow the investigated parameters to be optimally set to both increase mechanical properties as well as to minimize energy and material usage leading to minimized production costs.

Materials and Methods

Production and testing of the specimens

The A356 base material, with very low titanium and strontium contents (table 1), supplied by RHEINFELDEN ALLOYS GmbH & Co. KG (Rheinfelden, Germany), was melted using a 5.5 kW 7 kg resistance furnace (Nabertherm GmbH, Lilienthal, Germany) at a furnace bulk temperature of 800 °C in a SiC crucible (Aug. Gundlach KG, Grossalmerode, Germany).

Table 1. Chemical composition of the A356 base material in weight percent.

Si	Mg	Cu	Mn	Ti	Sr	Fe	Al
7.32	0.38	0.002	0.003	0.003	0.0004	0.09	rest

After the aluminum reached a temperature of 740 °C, the preheated modification agent was added as AlSr10 rods (KBM Affilips B.V., Oss, Netherlands). After 20 minutes, the preheated grain refining agent AlTi5B1 master alloy was introduced to the melt in form of rods (KBM Affilips B.V., Oss, Netherlands). Following grain refining, the hydrogen content of the melt was measured with the aid of a partial pressure-density testing device (mk Industrievertretungen GmbH, Stahlhofen a. W., Germany) and, on reaching a density index greater than 1.5 %, the melt was degassed by introducing argon 4.6 to the base of the crucible using a graphite lance (HASCO Hasenclever GmbH + Co KG, Lüdenscheid, Germany). When the hydrogen content and the particular casting temperature was stable, the melt was stirred and then cast with the aid of a pouring spoon into a Diez die, which was preheated to the specified mold temperature with the aid of an

oil heating system. The die was coated with graphite in the area of the specimen and with an insulating coat in the area of the feeders according to norm P 372 of the Association of German Foundrymen (VDG). 45 seconds after casting, the specimen was removed. The quality of the melt was controlled by thermal analyses and spectrometer measurements. 10 specimens per test run were cast, whereof 5 specimens were heat treated according to a T6 treatment (530 °C|6 h, water quenching, 165°C|8 h).
From 4 cast rods, d_0 = 8 mm tensile specimens were machined according to DIN EN 50125 and tested with the aid of a 8033 Instron tensile testing machine using a cross head speed of 0.35 mm/s according to DIN EN 10002.
Metallographic sections were prepared from 3 different positions of one as-cast rod per test run; representing 3 different cooling rates (position A is the highest, position C is the lowest rate), by embedding the specimens in Araldit combined with the hardener Ren HY 956 (both from Huntsman, Germany). The specimens were grinded using abrasive paper (320 to 1000 grades) and polished using a VibroMet (Buehler, Düsseldorf, Germany) machine. Optical micrographs were taken at different magnifications using the Axio Imager A1 m (Carl Zeiss, Oberkochen, Germany) light microscope. These images were analysed with respect to the number and the area of eutectic silicon particles using the image analysis software Axiovision (Zeiss, Oberkochen, Germany). The DAS was manually determined from the 50x magnified micrographs according to the Association of German Foundrymen's (VDG) Norm P 220; the average grain size was manually measured from the 50x magnified micrographs taken from metallographic sections which were etched according to Barker (figure 1).

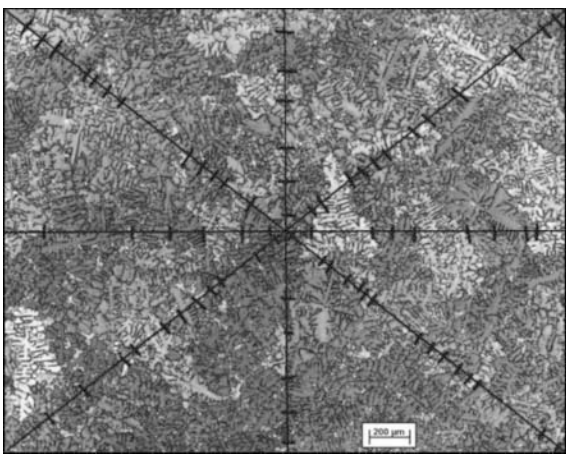

Figure 1. Grain size analysis of a metallographic section of test run 11 (table 2).

Setting of the parameters

To show the single and interaction effects of the specified parameters on the mechanical properties of A356, two settings for the die temperature and three settings of the remaining parameters were defined. The lower die temperature was set to 190 °C to ensure a complete mold filling without cold runs. The upper die temperature was set to 290 °C in order to produce an appropriate difference to the lower setting. The lower and mean casting temperatures of 690 °C and 720 °C represented a typical overheating for the used alloy [19, 24]. The upper casting temperature was set to the maximum of 750 °C to avoid marked hydrogen absorption by the molten aluminum and thus prevent gas porosity in the castings [25]. Besides the mean value of 0.20 wt.%, a titanium content of 0.05 wt.% and 0.35 wt.% was chosen to show the influence of an assumed too low and too high titanium content, respectively. The strontium content was varied from 50 ppm to 200 ppm and 350 ppm.

Design of experiments

A full factorial design prescribes a minimum of 54 test runs for the analysis of the single effects. To minimize the number of test runs and specimens as well as to visualize the interaction between the parameters, an orthogonal L18 Taguchi array was chosen. By using 18 test runs, this array enables both the analyses of the single effects of the chosen parameters as well as that of the interaction between the die temperature with both the titanium content and with the strontium content [26]. Table 2 summarizes the adopted L18 array.

Table 2. Orthogonal L18 Taguchi array with the settings of the individual test runs.

test run	die temp. (A) [°C]	titanium content (B) [wt.-%]	inter-action A/B (C)	strontium content (D) [ppm]	inter-action A/D (E)	casting temp. (G) [°C]
1	190	0.05	1	50	1	690
2	190	0.05	2	200	2	720
3	190	0.05	3	350	3	750
4	190	0.20	1	50	2	750
5	190	0.20	2	200	3	690
6	190	0.20	3	350	1	720
7	190	0.35	1	200	1	720
8	190	0.35	2	350	2	750
9	190	0.35	3	50	3	690
10	290	0.05	1	350	3	720
11	290	0.05	2	50	1	750
12	290	0.05	3	200	2	690
13	290	0.20	1	200	3	750
14	290	0.20	2	350	1	690
15	290	0.20	3	50	2	720
16	290	0.35	1	350	2	690
17	290	0.35	2	50	3	720
18	290	0.35	3	200	1	750

The results of the tensile tests and the microstructure measurements were analyzed and evaluated with the aid of the statistical methods analyses of means (ANOM) and analyses of variance (ANOVA). The ANOM indicates the direction of optimization of the factors, in which the mean deviation from the total average caused by every factor level shows the main effect of every single factor level. Using the ANOVA, the statistical significance of an effect of a parameter on the command variable can be evaluated. For this, the total result is divided into single variances. The variance expresses the squared deviation of the particular average [27].

Experimental Results

In its as-cast state, the die temperature mainly affects the material's tensile strength and the elongation at fracture (table 3). By decreasing the die temperature from 290 °C to 190 °C, the A356's tensile strength and elongation at fracture are significantly increased (figure 2). The image analyses show that this effect can be attributed to the influence of the reduced die temperature on the DAS and the size of the silicon particles (table 4 and figures 3 and 4a). With decreased die temperature and the associated increased cooling rate, the DAS and the silicon particle sizes are decreased which, according to the literature, lead to increased mechanical properties [20-23]. Except for very high cooling rates (position A), the grain size is not significantly influenced by a decrease in the die temperature (figure 4b).

Table 3. ANOVA results of the tensile tests. Tabulated critical f-value is 4.08 for the die temperature and 3.23 for the remaining parameters (95 % confidence level). Significant factors are highlighted.

f-value	tensile strength F	tensile strength T6	elongation at fracture F	elongation at fracture T6
die temp. (A)	25.23	3.27	20.91	2.83
titanium content (B)	3.79	2.78	1.44	1.17
interaction A/B (C)	0.15	0.31	0.47	0.75
strontium content (D)	5.34	1.76	10.77	0.34
interaction A/D (E)	2.95	2.41	0.76	2.10
casting temp. (G)	0.88	1.33	0.42	1.04

Table 4. ANOVA results of the microstructure analyses. Tabulated critical f-value is 4.45 for the die temperature and 3.59 for the remaining parameters (95 % confidence level). Significant factors are highlighted.

f-value	DAS			grain size		particle size		
position	A	B	C	A	B	A	B	C
die temp. (A)	11	8	6	17	13	52	71	49
titanium content (B)	1	3	1	2	36	5	6	14
interaction A/B (C)	1	0	2	6	21	8	17	13
strontium content (D)	1	3	2	1	11	70	61	91
interaction A/D (E)	4	1	0	1	22	9	5	6
casting temp. (G)	2	1	0	1	0	25	32	41

In its T6 state, the mechanical properties of the A356 are not significantly influenced by the die temperature (table 3, figure 2).
The grain refinement treatment with titanium causes a significant decrease in the grain size at mean cooling rates (position B), which leads to a significantly increased tensile strength in the as-cast state (table 3 and 4, figure 5). The analysis of the influence of the titanium content's single effect indicates that 0.20 wt.% titanium is the optimum for effectively refining the α-aluminum solid solution at a mean cooling rate (position B, figure 5b) and for producing the maximum tensile strength in the as-cast state (figure 5a). At a mean cooling rate, lower titanium contents do not lead to the minimum possible grain size and thus produce a lower tensile strength; higher contents lead to intermetallic titanium phases (table 4, particle size) which disturb the microstructure and thus could lead to a decrease in the tensile strength [28].

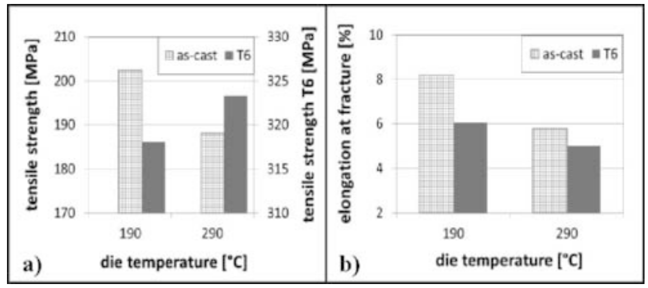

Figure 2. Influence of the die temperature on a) the tensile strength and b) the elongation at fracture of A356.

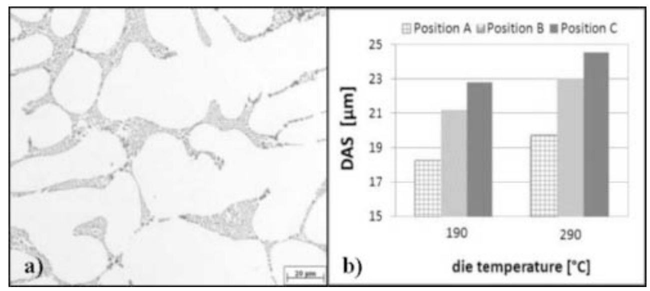

Figure 3. a) Fine eutectic silicon particles (black phase) in α-aluminum solid solution (white phase) of a specimen from test run 5, position A. b) Influence of the die temperature on the DAS of A356.

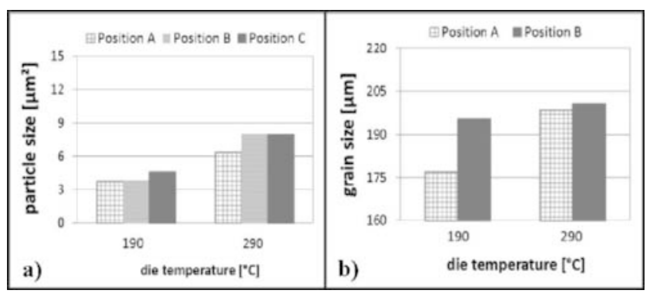

Figure 4. Influence of the die temperature on a) the grain size and b) the silicon particle size of A356.

According to figure 5b), it can be assumed at this point that there is an interaction between the die temperature and the titanium content, because when a higher cooling rate is present (position A), a higher titanium content is needed for the grain refining effect. The DAS and silicon particle size as well as the elongation at fracture is not or only slightly influenced by the titanium addition in the as-cast state as are all mechanical properties in the T6 state.
The influence of the interaction between the die temperature and the titanium content on the tensile strength and elongation at fracture of the as-cast A356 is shown in figure 6. With a decreased die temperature, the minimum grain size and the maximum tensile strength and elongation at fracture can be produced using the lower titanium content of 0.05 wt.% (figure 7). Moreover, when a low die temperature is used, the danger of an over-treatment is significantly decreased and thus a decrease in

the mechanical properties is avoided (figure 6). When a higher die temperature has to be employed, the maximum tensile strength and elongation at fracture can be achieved by using a mean titanium content which corresponds to the single effect of titanium (figures 5 and 6). Here, too much titanium leads to a significant decrease in the tensile strength. In the T6 state, there is no influence of the interaction between die temperature and titanium.

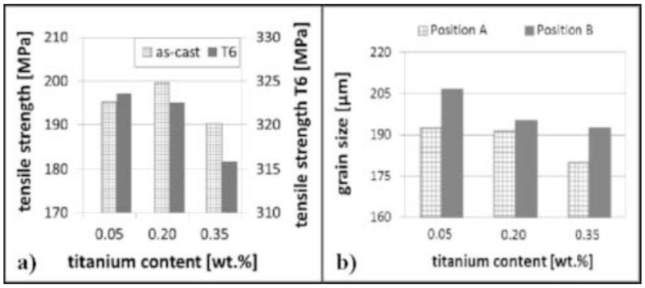

Figure 5. Influence of the titanium content on a) the tensile strength and b) the grain size of A356.

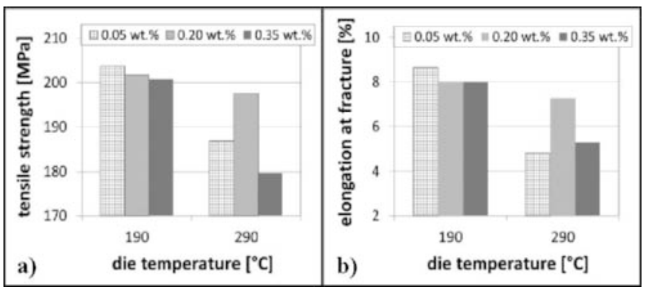

Figure 6. Influence of the interaction between die temperature and titanium content on a) the tensile strength and b) the elongation at fracture in as-cast state of A356.

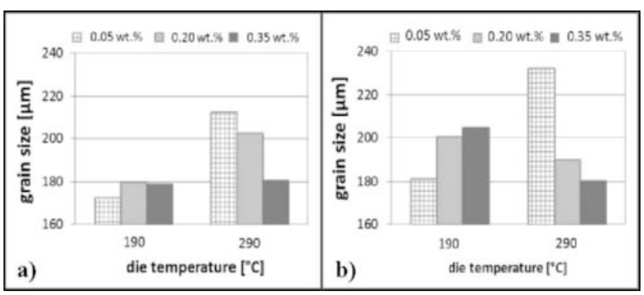

Figure 7. Influence of the interaction between die temperature and titanium content on the grain size of A356 in dependence of the cooling rate a) position A and b) position B.

The addition of strontium in the as-cast state leads to a significant increase in tensile strength and elongation at fracture of A356 (table 3, figure 8). In contrast to the addition of titanium, there is no negative influence of an over treatment with strontium. Although the maximum mechanical properties are reached with mean strontium contents, there is no decrease in tensile strength and elongation at fracture when a high content of strontium is present in the A356 castings.
The effect of strontium on the mechanical properties in the as-cast state is related to its influence on the silicon particle size, which is significantly decreased by strontium (figure 9a). Moreover, the grain size seems to be slightly influenced by the strontium addition (table 4). The DAS is not significantly influenced by strontium (figure 9b).
As to be expected, in the T6 state strontium has no significant influence on the mechanical properties (table 4, figure 8).

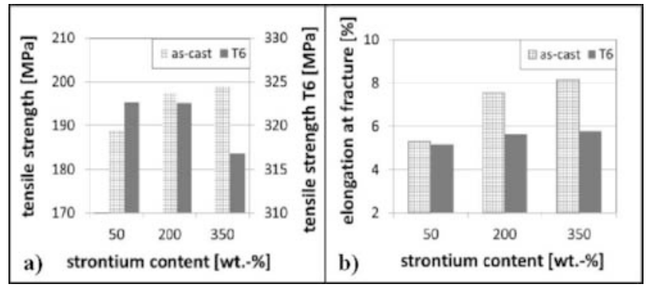

Figure 8. Influence of the strontium content on a) the tensile strength and b) the elongation at fracture of A356.

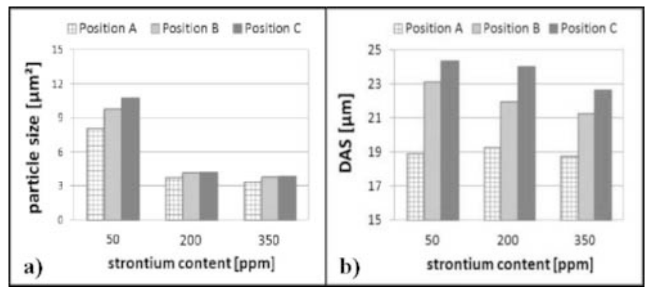

Figure 9. Influence of the strontium content on a) the silicon particle size and b) the DAS of A356.

Due to their interaction, a higher tensile strength can be produced with low strontium content when the die temperature is decreased (figure 10). The best strength value is reached with low die temperature and mean strontium content.

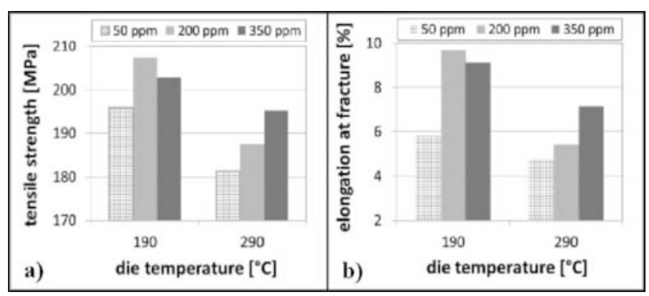

Figure 10. Influence of the interaction between the die temperature and the strontium content on a) the tensile strength and b) the elongation at fracture in the as-cast state of A356.

With increasing strontium content, the DAS slightly decreases, whereby the strongest decrease is achieved in combination with a low die temperature (figure 11a). The size of the eutectic silicon particles is influenced by the die temperature/ strontium interaction in the same way. For a given die temperature, the particles size can be further reduced with increased strontium content (figure 11b). The grain size is also significantly influenced (table 4).

The casting temperature has a significant influence on the microstructure in the chosen process latitude (particle size, table 4), but this effect is not strong enough, to effect the mechanical properties of die-cast A356 (table 3).

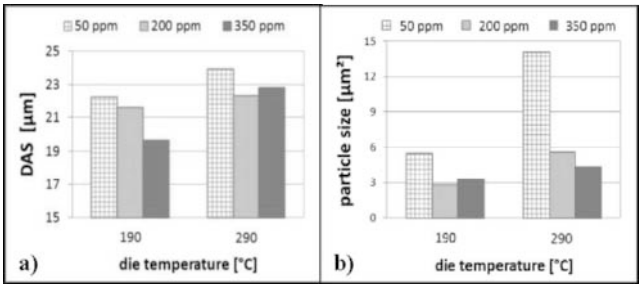

Figure 11. Influence of the interaction between the die temperature and the strontium content on a) the DAS and b) the silicon particle size of A356.

Modeling and Reference Test

With the aid of the present results, the influence of the investigated process parameters on the tensile strength can be expressed by a regression calculation:

R_m = 218 – 1.40E-01 * die temp. – 16.85 * titanium content + 3.46E-02 * strontium content + 9.26E-03 * casting temp. + 2.66E-02 * die temp.*titanium content – 1.19E-09*die temp.*strontium content [MPa] (eq. 1)

To confirm this equation and the testing results, a verification test run was conducted. The settings for the parameters, the calculated result and the measured average result of the tensile tests are summarized in table 5.

Table 5. Settings for the verification test run and the calculated (cal.) and measured (m.) tensile strength.

die temp. [°C]	titanium content [wt.%]	strontium content [ppm]	casting temp. [°C]	cal. R_m [MPa]	m. R_m [MPa]
190	0.05	200	720	**204 ± 14**	**195 ± 6**

The measured average tensile strength (195 MPa) is located within the confidence interval of the calculation (204 MPa ± 14 MPa). This emphasizes the quality of the prediction and of the results above. Analyses of the fracture surfaces show that some oxides are located within the tensile specimen, which could be a reason for the location of the measured average tensile strength in the lower range of the confidence interval.
Generally, the tensile strength in the as-cast state can be considered as relatively high since the European Norm DIN EN 1706 for an AlSi7Mg in the as-cast state gives a tensile strength of 170 MPa.

Discussion

The specified variations of the die temperature, casting temperature, titanium and strontium contents permitted the intended investigation of the single and interaction effects of these parameters on the properties of an as-cast and a T6 treated A356 to be carried out.

Generally, it can be shown that these process parameters have no significant influence on the mechanical properties of A356, when this material is heat treated accordingly to a T6 regime. It seems that the effects of the DAS, grain size and silicon particle size are dominated by the age hardening and the spheroidized silicon particles produced by the T6 treatment [29].
In the as-cast state, the investigated process parameters influence the microstructure and mechanical properties of A356 to a great extent. Especially the die temperature shows a substantial influence on the microstructural and hence on the mechanical properties of the A356 in the as-cast state. Besides improving the mechanical properties, a decreased die temperature improves the grain refining effect of titanium and the modification influence of strontium. The die temperature significantly influences the DAS, grain size and the size of the eutectic silicon particles. Titanium influences the grain size and the size of the eutectic silicon, and strontium has a big impact on the size of the eutectic silicon size but only a slight effect on the grain size. This effect of the decreased die temperature is related to the increased cooling rate. According to [20], the increased cooling rate leads to an increased nucleation temperature, nucleation undercooling temperature and solidification range leading to an increased number of nuclei which affect the grain size and the DAS.
Since the addition of titanium in the present framework has no significant influence on the elongation at fracture, it can be assumed that this mechanical property does not depend on the present grain size in this investigation of the A356 microstructure.

Conclusions

Due to industrial and social necessities, the fuel consumption as well as the emissions of automobiles has to be reduced. One key to realize these challenges is to downsize automotive casting parts. This demands an optimization of given casting materials.
The mechanical properties of the much used light metal alloy A356 can be optimized if a lower die temperature can be employed. The resulting increased cooling rate leads to smaller DAS, grain size and silicon particles, which induce increased mechanical properties. Moreover, the refining and modification effect of titanium and strontium is increased by lowering the die temperature leading to reduced energy and material costs.
If, due to the resulting mechanical properties, a T6 heat treatment is required for an A356 casting this cast device can be produced using low casting and die temperatures, and reduced titanium and strontium contents; where the actual wall thicknesses allow these settings.

Acknowledgments

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