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1 Introduction

The use of aluminum has increased over the years and has resulted in an increase of recycling also. These recycled aluminum alloys are called secondary alloys and do not display as good mechanical properties as primary aluminum alloys. This is the result of elevated amounts of impurities in these alloys such as Fe and Copper (Cu). In order to improve the properties so called modifiers are added that modify the Fe phases to make them less harmful. Mn is one of these and is frequently used for this purpose, due to its cost-effective and environmental friendly properties. Our task was to examine the influence of Mn on an Al-Si alloy with a relatively high level of only Fe in it. This task was given to us by the Institution of Component Technology at the School of Engineering in Jönköping. The work consisted of casting test bars, analyzing chemical compositions, testing mechanical properties, studying the microstructure and performing a literature survey.

1.1 Purpose and Goals

The purpose of this work was to develop recyclable aluminum cast alloys, so that tensile strength, ductility and other sought after properties can be improved substantially. Mn is added to our alloy and increased gradually in order to be able to find the optimal amount. By doing this we can find a good composition of the included materials in the alloy and also find out how heat treatment affects the mechanical properties.

The goal is to: cast test bars to be pulled in the tensile test machine, analyze their structure through a microscope, perform heat treatment on half the test bars, gain a deep theoretical knowledge about Fe and Mn and their influence on aluminum alloys and be able to optimize the properties with the right amount of Mn.

1.2 Limitations

The project has the following limitations:

- Alloys other than Al-9.5%Si with 200ppm Sr in it will not be studied.
- Only a hypoeutectic composition will be studied.
- Only insignificant amounts of Mg, Zn and Cu will be included in the alloys and the maximum amount of Mn will not exceed 1%.
- Tensile tests are performed in room temperature only.
- Superheating will not be used; all bars are cast at the same temperature.
- No other heat treatments other than T6 will be carried out; also the microstructure of the heat treated bars will not be studied.

2 Literature Survey

2.1 Background

Aluminum comes from the word alun, a name given to a composition of aluminum which was used for medical purposes by the Babylonians and Egyptians in the early first century [1]. It is believed that aluminum was used as early as 5000 BC, although not in its pure state. Clay containing aluminum was used for pottery during this time. It is found in the earths crust in the form of oxides and silicates and it was not until the 19th century that aluminum was reduced to its metallic form. In 1886 an aluminum refining process was invented by Hall and Heroult which made it affordable to produce commercial quantities [2].

Aluminum is ductile and has low strength in its elemental form, but combined with small amounts of other materials such as copper, iron, silicon, magnesium, nickel and zinc it can take on a variety of (improved) physical and mechanical properties. The greatest advantage of aluminum is its high strength-to-weight-ratio and corrosion resistance. These properties have given aluminum a great number of uses. "The important factors in selecting aluminum and its alloys are their high strength-to-weight ratio, their resistance to corrosion by many chemicals, their high thermal and electrical conductivity, their nontoxicity, reflectivity, and appearance, and their ease of formability and machinability; they are also nonmagnetic" [3]. Aluminum is used mostly in packaging and containers, other major uses are the transport industry and construction.

2.2 Cast Aluminum Alloys

The use and production of aluminum cast alloys has increased over the last decades, much do to its versatile properties that can be obtained through alloying elements and heat treatment. Aluminum cast alloys have until recently (1960's) mainly been used for low strength components as it is hard to control and eliminate defects that arise in the melt and solidification process. In the automotive and aerospace industry aluminum today has become a great substitute for heavier metals, and foundry methods have gradually improved enough to assure that the higher demands on mechanical properties are met. Problems still exist in the casting process however.

Casting is a complex procedure. A number of important factors have to be considered; the casting method, alloying elements, cooling, reaction of the melt with its surroundings, shrinkage, Secondary Dendrite Arm Spacing (SDAS), mould material and shape of the component to be cast are to name a few. SDAS is the distance between the branches that form on the dendrites. See figure (6b) for a clear picture of SDAS.

Altering the microstructure and/or structure development of the melt of an aluminum cast alloy will change the mechanical properties. This can be done by adding modifying elements to the alloy. Strontium, Manganese, Sodium and Beryllium are examples of these. Changing the solidification rate will also drastically change mechanical properties. Solidification time greatly affects SDAS. Defects arise when SDAS is large; as the dendrite arms grow together they block the melt from reaching inner parts which in turn creates porosity in the casting. When a casting solidifies quickly the dendrites do not have time to grow, resulting in a finer structure and less porosity [2, 4].

2.3 Aluminum Silicon Alloys

Aluminum alloys are divided into groups according to major alloying elements. More information on this can be found in appendix A. Al-Si is the most common alloy system used in foundry today, they are classified into hypoeutectic, eutectic and hypereutectic alloys depending on the amount of Si. The eutectic composition is around 12.7% Si. Alloys with more than 12.7% Si are called hypereutectic and alloys with less are called hypoeutectic. Common Si rates range from 5-23%.

Si is used in cast alloys mainly because it increases the fluidity of the melt, compensates for shrinkage during solidification, and decreases the melting temperature. Silicon is also one of the few materials that can be added to aluminum without increasing its weight. However, unmodified Al-Si alloys do not display great mechanical properties, especially if the solidification rate was slow; this is because the Si phase becomes coarse and brittle. Strontium is commonly added to modify the silicon phase, giving it a finer structure.

The most common impurity in Al-Si castings is Fe, which preferably is kept as low as possible. Fe comes both from the manufacturing process of primary aluminum and also from melt reactions during recycling. There is no cheap way to remove the Fe although these methods do exist. A method called electromagnetic filtration can be used to get Fe down to 0.3-0.4%. It is worth mentioning that small amounts of Fe are needed to keep the casting from sticking to the die and therefore should not be removed completely.

There are two major problems associated with high Fe levels:

1. Porosity due to blocked feeding
2. Low ductility due to the initiation of cracks in iron needles

During solidification large Fe plates develop called the β-phase (Al_5FeSi) which prevents feeding; solidification shrinkage then creates porosity. These plates can also be seen as needles when studied in two dimensions. The needles have a brittle nature and cracks tend to start and spread through them.

There are a few ways to deal with this but the most common and economical way is the addition of modifiers to neutralize the iron plates. These modifiers promote the formation of the finer alpha phase, also called Chinese script morphology $Al_{15}(Fe,Mn)_3Si_2$. A frequently used modifier is Mn. Opinions vary on the effect that Mn has on Fe and no specific formula exists giving the ratio of Mn/Fe for a given alloy. A common rule of thumb is a ratio of 0.5 Mn/Fe. It is of interest therefore to determine exactly what the effect of Mn is on Fe without the effects of other elements and also which ratio will benefit the mechanical properties the most [4-8].

2.4 Phases of Al-Si alloys containing Iron and Manganese

There are two phases present in Al-Si alloys; the primary phase of aluminum or silicon, and the eutectic phase consisting of both [7]. Two more phases are present when Fe is included in the alloy. An alpha phase(α) and a beta phase(β). These are called intermetallic phases. The chemical name will not be included here, it is enough to know that the α-phase forms a denser, finer structure benefiting the mechanical properties and the β-phase forms a plate-like structure which is detrimental to the mechanical properties, see figure1 below [9].

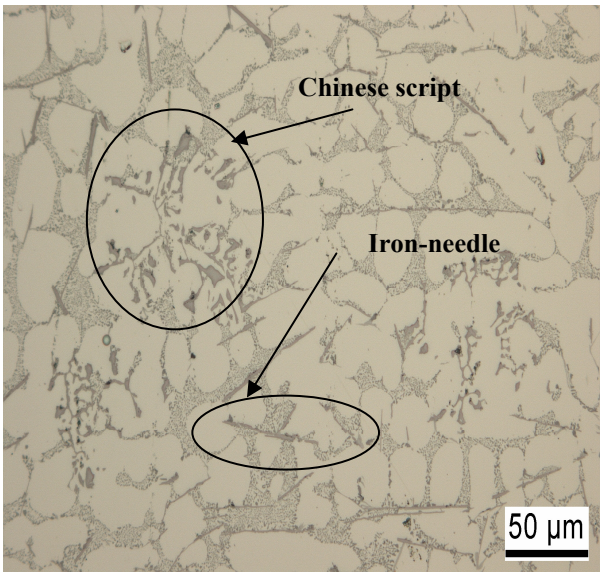


Figure 1 Chinese script and iron needles [9].

John A. Taylor writes in one of his articles that the time at which the different phases form is important. If the intermetallic particles are formed before the primary phase solidifies, they will grow and become much larger than if they had formed after the dendrites solidified. The growth of these particles occurs in the liquid and is hindered by solidified parts, so the later they form the less they grow. According to Taylor, increasing the Mn and Fe content will result in early formation of these phases. Slow cooling rates will also result in large intermetallic particles since they have more time to grow [7].

2.5 Manganese in cast aluminum alloys

Mn is added to alloys containing Fe in order to hinder Fe's poisoning effect on Al-Si eutectic nucleation sites [7].This results in a finer eutectic structure, greater fluidity and less porosity. Mn is also added to change the morphology of the Iron phases to a rounder structure called Chinese script morphology. There are two types of Chinese script as was mentioned earlier, depending on the alloy composition. According to Prigunovas research, Mn transforms the beta needles to more branch-like and compact crystals which in turn lead to increased strength and ductility. Mn is also believed to reduce FeAl and its pitting effect. Taylor shows that porosity decreases with the help of Mn in an Al-Si alloy. 0.5% Mn was added to a 1% Fe Al-9Si alloy which resulted in a decrease of porosity to the level of an alloy with only 0.6% Fe [7, 10].

In order to ease machinability the total amount of Mn and Fe should not exceed 0.8% [11]. Elongation of non heat-treated alloys (F Temper) is best with values between 0.5% and 0.8% Mn. This gives an elongation of about 9%. For heat-treated alloys elongation is somewhat higher, about 13%. The ultimate tensile strength stays basically the same around 300MPa throughout varying levels of manganese, for temper F treated alloys. Yield strength for temper F was 150Mpa and also did not vary much. After heat treatment (T6) the UTS was just below 300Mpa and YTS was around 200Mpa. They concluded that no improvement of strength could be expected for Mn contents exceeding 0.5% [12].

2.6 Manganese and pre-heat treatment

An investigation from Shenyang in China shows an interesting method to increase tensile strength and elongation. First they pre-heat the melt aluminum to 850 °C and hold it for 2 hours. Then decrease the temperature to 650 °C and add the Mn. The conclusion was that tensile strength and elongation improved by 40 to 80 Mpa and 6% to 7%, respectively [13].

2.7 Iron in cast aluminum alloys

Taylor suggests in one of his articles that the critical level of Fe depends on the Si content of the alloy; if the critical level of Fe is reached the growth of β-needles is too unconstrained. Higher Si contents decreases the time allowed for needle growth which is why more Fe can be tolerated in these alloys. The critical point for Al-9Si is about 0.6% Fe. When taking a closer look at a pressure die-casting alloy called Castasil-37, the Fe content is held under 0.15% to reduce the number of harmful Fe needles. Mn replaces the Fe in order to get good ejection behavior and prevent die soldering [7, 12].

2.8 Pores in aluminum alloys

Manganese has some influence on pore fraction. Taylor [7] measured pore fraction depending of Fe content. At 0,3 % Fe there was less than 1 % pore content. Pore fraction increased to 1,4 % at 1 % Fe. When 0,5 % Mn was added to 1 % Fe the porosity decreased to 1 %. The conclusion was that the effect of Mn reduced the fracture of pores to the same level as 0,6 % Fe (the critical Fe content for that composition). He also says that Mn does not always reduce porosity, especially at higher Fe content. Another author can't see any significant change in casting porosity level when adding Mn [14].

Carles & Nestors [15] investigation shows that pore fraction depends mostly on the cooling rate. At the fastest cooling rate they found the smallest pores and least fraction.

Hydrogen is a common problem in foundries. When furnaces stay cool the linings take up hydrogen from the surroundings. Later when the furnace is heated up and in use, hydrogen may cause higher pore content in the final cast product. It can take days to get rid of that hydrogen in a furnace. Wet gases are also another source to delivery of hydrogen into the casting [16].

Another possible cause of pores is bifilms. Bifilms are formed when surface films are folded into the melt. These bifilms are folded over several times and gas often becomes trapped in the folds of the bifilm. The gas inclusions expand and become larger with slower cooling rates; eventually if enough time is given they expand enough to become fully inflated like a balloon. Campbell has a theory on why pressure die castings have superior properties. He says that the surface tension increases when a bubble surface is squeezed into interdendritic spaces. As the SDAS becomes smaller, the gas pores cannot squeeze in-between the dendrite arms. There is not enough room for the bubble to grow. The microstructure is finer and therefore shows better properties [16].

2.9 Strontium in cast aluminum alloys

The main reason for modifying with strontium is to obtain a finer structure of the Si particles and also the Si becomes more round. Dong [17] writes that with 200ppm Sr in a Al-7Si alloy the Si grains will decrease in size from 38 to 0.8 μm. According to literature [11], the Si content should be at least 5-7% in order for the modification to be useful.

9.5% Si was used in the alloy cast for this research; this is a common hypoeutectic composition, similar to alloys such as Silafont 09 (Appendix B) and Castasil-37 [12]. The latter is used for pressure die-casting. The Sr level is suggested to be 60-250 ppm. A diploma work written 2002 [18] shows that it is beneficial to add only 100 ppm Sr to obtain a finer structure. A coarser Si structure develops when too much Sr is added.

According to B.Closset [19] the Sr level should be between 50 and 150ppm. Over modifying is not as critical as under modifying when it comes to the mechanical properties of the alloy. B.Closset also writes that 200ppm Sr benefits elongation the most.

2.10 Heat treatment

Heat treatment is carried out to improve the strength of heat treatable aluminum alloys and usually consists of three steps:

1. Solution heat treatment
2. Quenching
3. Age Hardening

In the first step, the alloy is heated to a temperature just below the melting temperature (in the single phase region of the phase diagram). This is so that any hardening elements in the alloy will spread evenly through the structure.

In the second step, the alloy is cooled rapidly so as to "freeze" the properties obtained in the solution heat treatment. This is usually done by lowering the alloy into water. At this stage the material will be soft.

The third step is the hardening stage. Age hardening is done at a lower temperature than the solution heat treatment and held there for a longer time, the temperature depends on which treatment is chosen and in some cases room temperature is enough. This is called natural aging. This stage strengthens the grain structure. After some time the hardness will reach a peak, and thereafter decrease if aged for too long.

Aluminum alloys are divided up into families depending on the major alloying element used, as was mentioned earlier. 2xx, 3xx, 7xx and 8xx are heat treatable [3, 20].

T6 is one of the most common aluminium alloy heat treatments used on aluminum alloys.

3 Experimental Technique

3.1 Alloy chart

Six different alloys were cast in this experiment: See nomenclature (appendix C) for explanation of the different names. Three specimens of each alloy were cast to obtain more accurate results. Also, three different solidification rates were used for each alloy to simulate pressure die casting, gravity die casting and sand casting. Another batch was made for the heat treated bars; these were not studied through a microscope but were used in the tensile strength tests. The following chart shows the composition of each alloy. See appendix D for a complete chart of all elements.

Name	AL	Si %	Mg %	Fe %	Mn %	Sr ppm
A16MA		9,52	0,0047	0,096	0,0012	200
A16MB		9,13	0,0034	0,32	0,0078	200
A16MC		9,7	0,0022	0,31	0,1534	170
A16MD		9,27	0,0007	0,37	0,306	170
A16ME		9,1	0,0012	0,37	0,68	160
A16MF		9,2	0,001	0,38	1,01	190

Table 1. The compositions of the alloys cast.

Only Fe and Mn are varied, and as stated before the purpose of this thesis was to investigate the effects of Mn on Fe. Mn is gradually increased and Fe is kept constant after A16MB.

3.1.1 Casting

The alloys were produced by adding Si, Fe and Mn to the Aluminum melt. When it comes to Fe and Mn they were added in powder form with a purity of 75% respectively; the remaining 25% is some kind of flux media. The resistance furnace was set to 750°C for melting of the pure Aluminum and the alloying elements were preheated in a preheating furnace to 200°C. The melt was always skimmed before any addition of an element. The materials were added in following order: Si, Fe, Mn and last Sr.

3.1.2 Composition

In order to determine the composition of the alloy that had been produced, coins, one at the start and another at the end of the casting, were cast and analysed. The coins were turned using a lathe, which gave them a plane surface so they could be used for analysis. When performing optical emission spectrometry the surface of the sample is placed on a plate that is protected from oxides with help of protection gas argon, Ar. Thereafter a bit of the surface is burned and the amount of the different elements is presented.

3.2 Gradient solidification

Bars were cast for the gradient solidification experiments. With gradient solidification techniques it is possible to achieve a cast free from oxide films and porosity defects. In this work a resistance-heated furnace with an electrically driven elevator was used, see figure 2. This equipment offers the possibility to control the solidification rate and direction of the remelted metal. When re-melting the bars, a bar was inserted into the furnace, enclosed within a graphite coated steel tube. The metal was remelted in a protecting atmosphere (Ar), which prevents oxidation. The furnace moved with a constant velocity, v, and the bar was continuously cooled in water. The water was

Figure 2 Gradient solidification furnace.

sprayed directly on to the steel tube. In this experiment 108 bars were cast. Three different velocities, v, were used, 0.03 mm/s, 0.3 mm/s and 3 mm/s. At every velocity, three bars were made. Fifty four of the bars were heated treated before tensile testing.

3.3 Heat treatment

The procedure of heat treatment that was conducted follows the sequences presented below:

1. Solution heat treatment for 6h at 520 degrees.

2. After solution heat treatment samples were quenched in water of 60 °C.

3. The final step is the warm aging of the samples for 8h at 165 °C.

After the heat treatment procedure the bars were prepared for tensile testing.

3.4 Mechanical property tests

3.4.1 Room temperature tensile testing

All bars that were produced were used to determine the room temperature tensile properties of the alloy. The kind of tensile specimen that was prepared for tensile testing is schematically shown below both before and after the preparation, see figure 3. The as-cast specimens were tested at least one week after they were produced, while the heat treated ones could be tested directly after the heat treatment process. The tensile tests were conducted using a tensile test device called Lloyd EZ50, see figure 4 below.

Turn was done to avoid breakage tip, which can easily arise when using square-shaped samples. Afterwards the turning operation sample had a waistline diameter of 7 mm and waistline length of 60 mm including radii of 5 mm at the end of the waistline length, on both sides. The reason for these measurements depends largely on accommodation to tensile testing equipment EZ50.

Tension was accomplished with increasing tension load until it resulted in fracture; the elongation rate was 0.5 mm/minute. Strain was measured using an axial extensometer with a gage length of 25 mm, see figure 4 below.

Figure 3. The preparation procedure.

The data in form of load and displacement was monitored and also stored and analyzed using Matlab to obtain ultimate tensile strength, yield strength, modulus of elasticity, elongation etc.

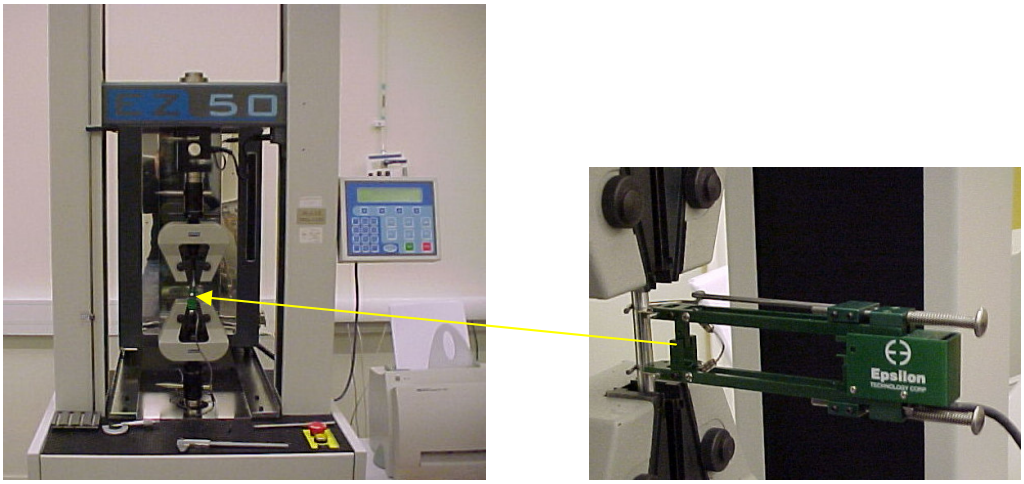


Figure 4. Tensile test machine Lloyd EZ 50. The right picture shows the extensiometer mounted on the tensile test specimen.

3.5 Microscopic examination

When the tensile tests were done, each of the specimens was prepared for microscopic examination. The preparation consisted of sectioning and mounting the specimens in a plastic medium to form a cylindrical piece, see fig 5, followed by grinding and polishing procedures of the specimens.

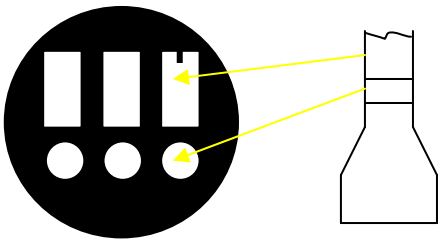


Figure 5. Specimens mounted in a plastic medium. The cuttings indicate the number of the specimen e.g. one cut corresponds to the first specimen followed by the second and third.

3.5.1 Observations

The phases have been identified by the color and morphology and compared to literature. No Energy Dispersive Spectrometry (EDS) analysis has been performed.

4 Results

4.1 The influence of Mn and cooling rate on the microstructure

4.1.1 SDAS

The following pictures were analyzed in an optical microscope in order to study the SDAS of the different alloys. Three pictures of each alloy are taken; one for each solidification rate, see figure 6. They can be seen as going from fine to coarse in that order. As observed, the solidification rate seems to be the most important factor. They all show the same SDAS for a given solidification rate, independent of the amount of Mn and Fe

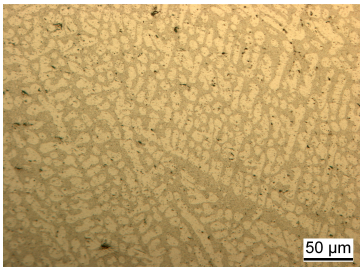
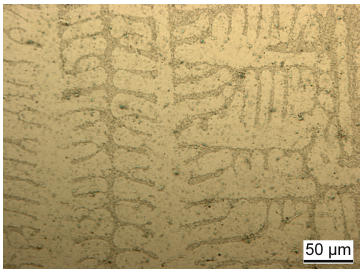
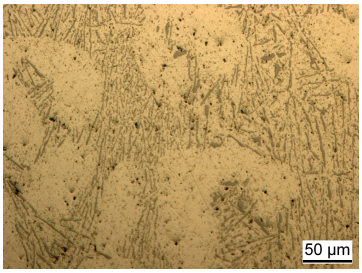
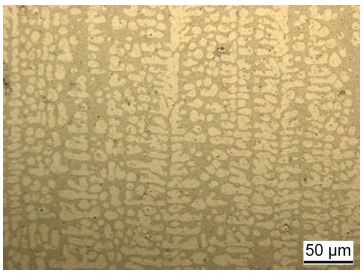
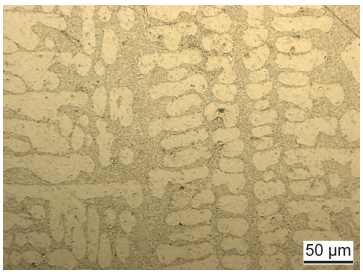
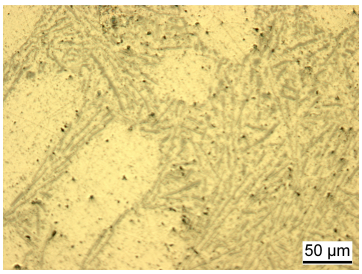
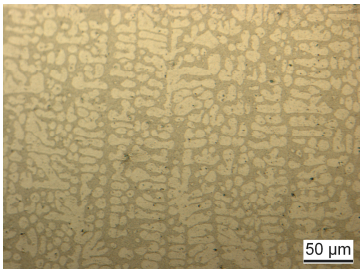
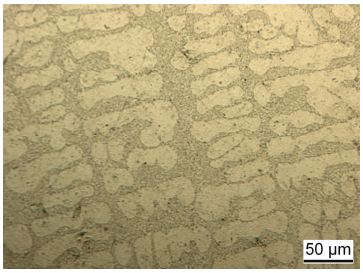
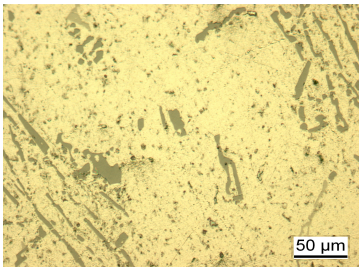
SDAS 10µm	SDAS 18µm	SDAS 48µm
		
(a) 0%Fe-0%Mn	(b) 0% Fe-0%Mn	(c) 0% Fe-0%Mn
		
(d) 0.3%Fe-0%Mn	(e) 0.3%Fe-0%Mn	(f) 0.3%Fe-0%Mn
		
(g) 0.3%Fe-0.15%Mn	(h) 0.3%Fe-0.15%Mn	(i) 0.3%Fe-0.15%Mn

Figure 6. (a-i) The microstructure for different cooling rates.

As demonstrated in figure 7, the solidification rate clearly has the greatest impact on the coarseness of the microstructure. The different levels of Mn did not seem to influence the dendrite cell size, neither did the Fe, see figure 7 (a-i).

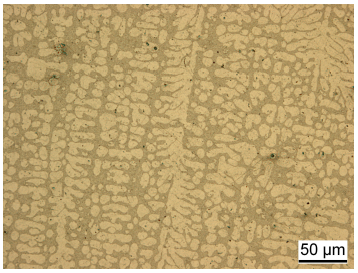
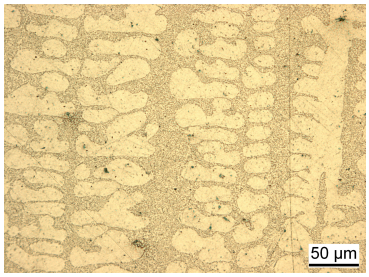
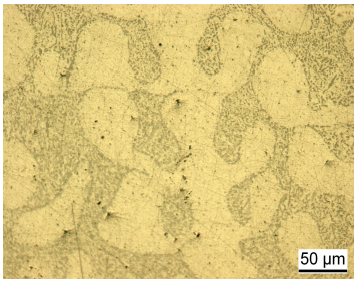
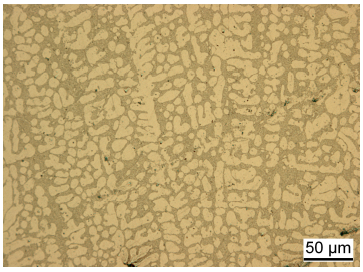
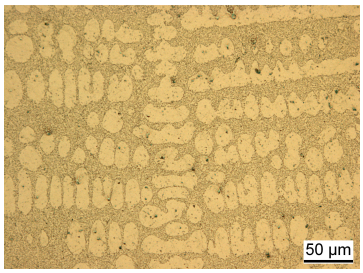
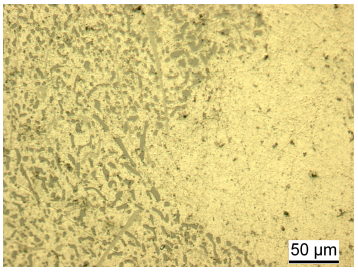
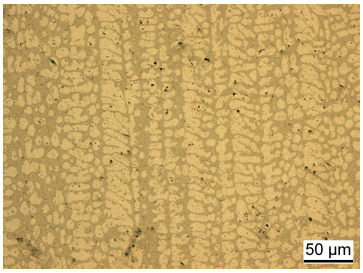
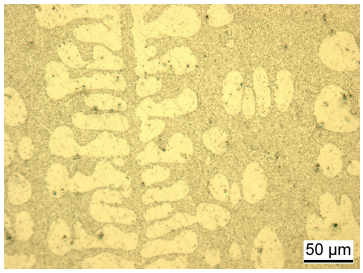
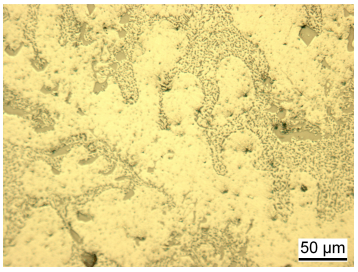
SDAS 10 µm	SDAS 18 µm	SDAS 48 µm
		
(a) 0.3%Fe-0.3%Mn	(b) 0.3%Fe-0.3%Mn	(c) 0.3%Fe-0.3%Mn
		
. (d) 0.3%Fe-0.6%Mn	(e) 0.3%Fe-0.6%Mn	(f) 0.3%Fe-0.6%Mn
		
(g) 0.3%Fe-1%Mn	(h) 0.3%Fe-1%Mn	(i) 0.3%Fe-1%Mn

Figure 7. (a-i) The microstructure for different for different cooling rates.

4.1.2 Intermetallics

Figure 8 shows intermetallic phases of the alloys at different cooling rates. The pictures illustrate how Mn affects the size of the needles.

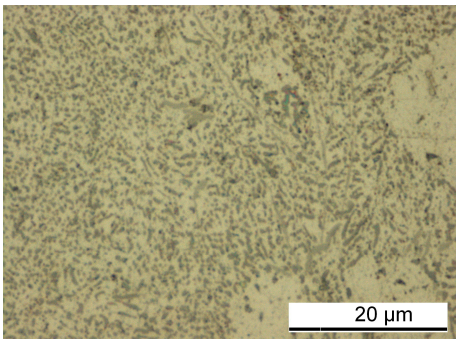
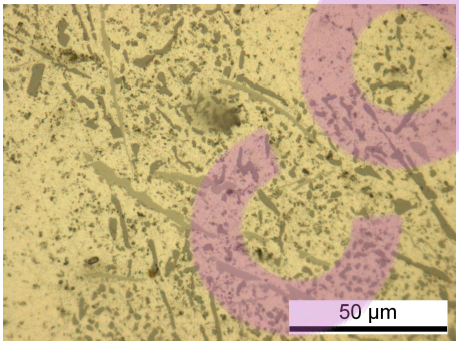
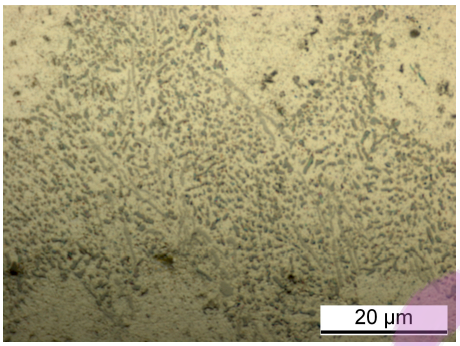
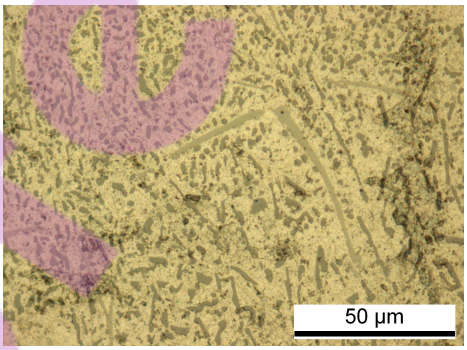
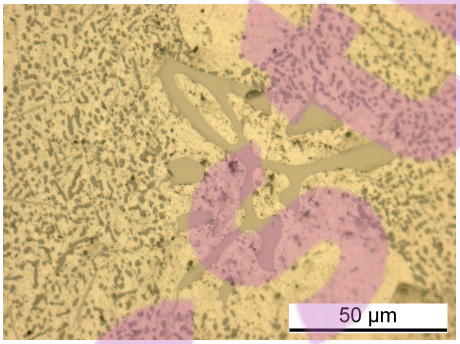
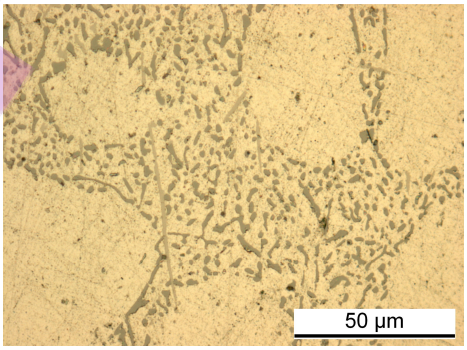
Iron needles and Chinese scripts	**Iron needles**
	
(a) 0.3%Fe-0%Mn, 100x Mg. SDAS 18 µm	(b) 0.3%Fe-0%Mn, 50x Mg. SDAS 48 µm
	
(c) 0.3%Fe-0.15%Mn, 100x Mg. SDAS 18µm	(d) 0.3%Fe-0.15%Mn, 50x Mg. SDAS 48µm
	
(e) 0.3%Fe-0.3%Mn, 50x Mg. SDAS 48 µm	(f) 0.3%Fe-0.3%Mn, 50x Mg. SDAS 48µm

Figure 8 (a-f) Intermetallic phases for different cooling rates.

The Fe needles are not visible for all cooling rates, the fastest speed did not allow enough time for needles to grow. Also the medium cooling rate is shown in 100 x magnifications for figure 8a and 8c. Only alloy F showed needles at SDAS 10µm. The location of the intermetallic regions is important to observe when evaluating these samples. This will be discussed later.

Each test from B-C shows that the needle length increases with slower cooling. Alloy D with 0.15% Fe and 0.15% Mn had both needles and Chinese script in the sample with slowest cooling, Fe needles dominated however. Notice in the picture above the Chinese sign is much larger than the needles.

Figure 9 shows alloy E and F. The alpha phases dominated these samples, and are compared to the sludge that also forms.

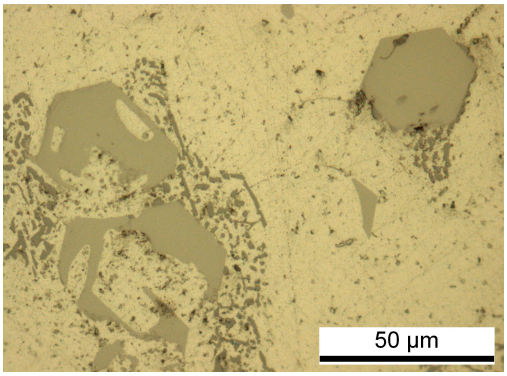
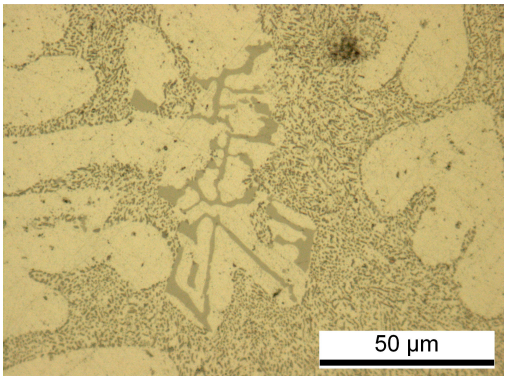
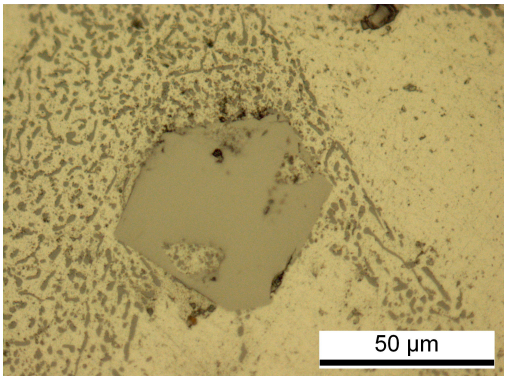
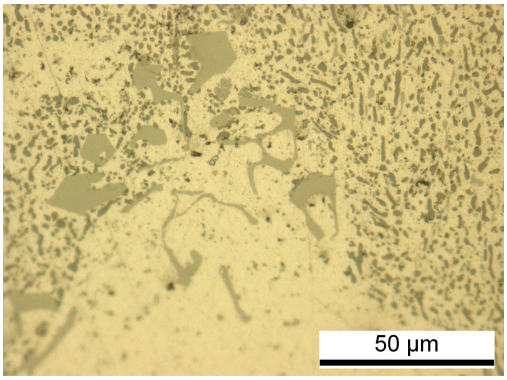
Sludge SDAS 48µm	**β-phases SDAS 48µm**
	
(a) 0.3%Fe-0.6%Mn 50x Mg.	(b) 0.3%Fe-0.6%Mn 50x Mg.
	
(c) 0.3%Fe-0.6%Mn 50x Mg.	(d) 0.3%Fe-0.6%Mn 50x Mg.

Figure 9 (a-d) Chinese script and sludge as observed in the microstructure.

Notice how large the sludge spots are compared to the Chinese script in fig. 9. Sludge spots cause problems with machining as they are harder than the rest of the matrix.

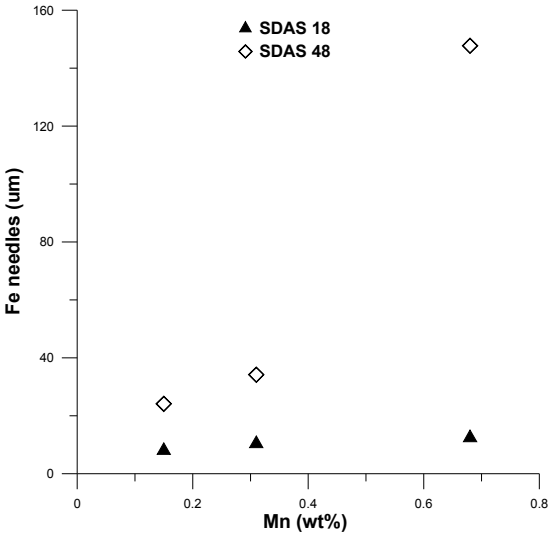
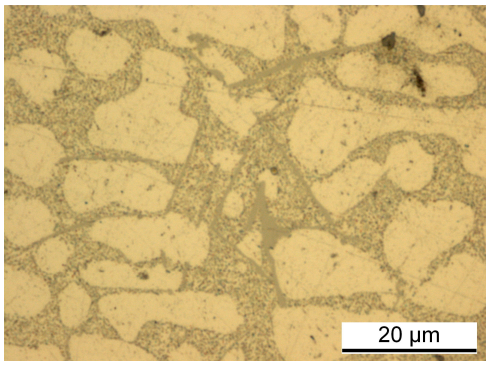


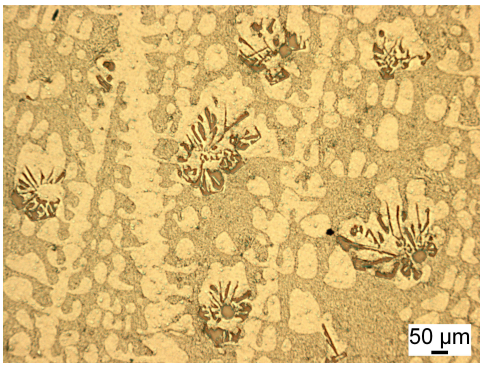
Figure 10 - The effect of Mn on Fe needles.

The graph (fig.10) shows an interesting trend in the last three alloys (MD-MF) at medium and slow cooling. The iron needles were found to increase in length with high Mn. The fastest solidification rate had needles visible in only one alloy and therefore was not plotted. This observation can perhaps be explained by the timing of the formation of the needles as was discussed before in the literature survey. The location of the needles gives a clue as to when they were formed. Intermetallic phases found in the dendrites must have been formed before the dendrites solidified (fig.11b), which is harmful as the intermetallic phases will grow much bigger then. It seems that higher Mn levels cause earlier formation of the intermetallic phases.

Figure 11(a-b) shows the alloy MF first at 100x Mg. and then at 5x Mg. for the slowest cooling. Even though there is 1% in this alloy the needles were still present, meaning that they are not completely suppressed. Figure 11(b) shows an example of what was discussed earlier about the location of the Chinese scripts with increased Mn levels.



(a) 0.3%Fe-1%Mn 100x Mg.



(b) 0.3%Fe-1%Mn 5x Mg.

Figure 11. Needles and Chinese script in the same alloy containing 1% Mn.

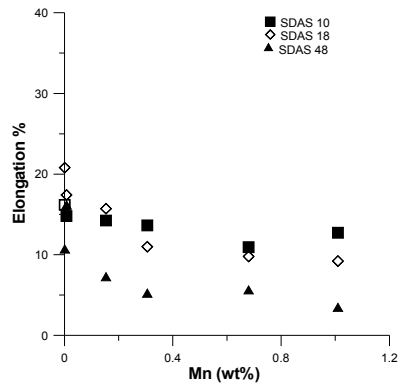
4.2 The influence of Mn and cooling rate on the mechanical properties

The following graphs illustrate the influence of Mn on the mechanical properties of the different alloys (see appendix E for values used). The graphs are shown in as-cast and heat treated form, next to each other. An interesting notation is that Mn only improves the properties overall for UTS, YS and K, but not significantly. Note also that alloy A containing 0.1%Fe and alloy B containing 0.3% Fe do not differ much from each other, indicating that 0.3% iron may be an acceptable level for casting, where Mn is not needed for modification.

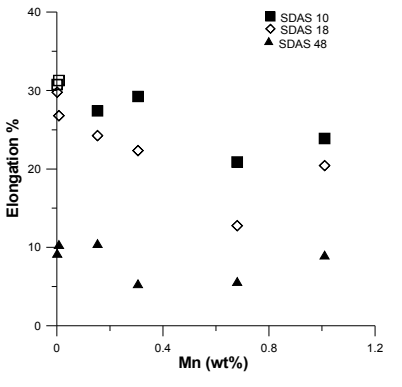
4.2.1 The effect of Mn on Elongation

As cast

Figure 12(a) shows how elongation is influenced by Mn content for as-cast test bars. The effect of Mn is roughly the same as heat-treated but with lower elongation values for all the samples.



(a) As Cast



(b) HT

Figure 12 (a-b) The effect of Mn on Elongation

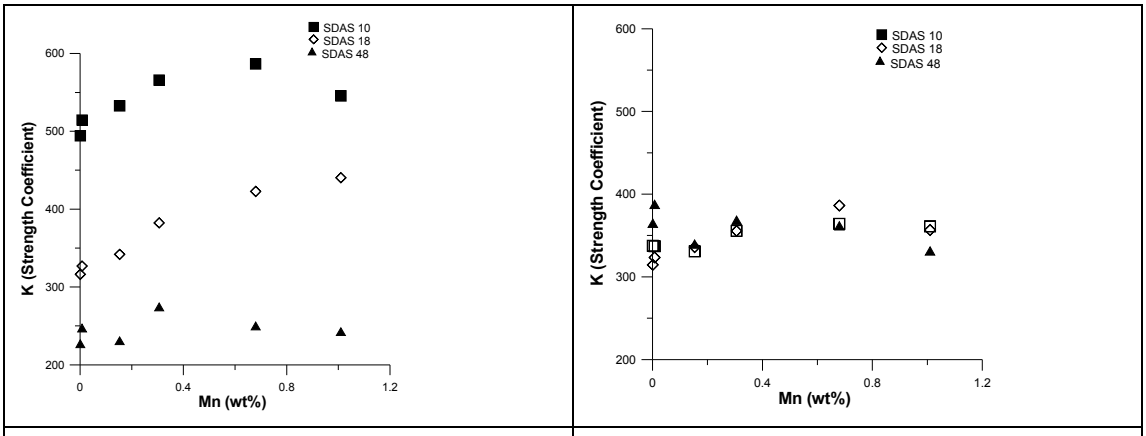
Heat treated

Figure 12(b) shows the relation between elongation and Mn content for heat-treated test bars. At faster solidification speeds (SDAS 10 µm) the elongation is highest and the effect of Mn on Fe improves the elongation first at a Mn content exceeding 0.6 %. Overall however, Mn decreases elongation. The first two alloys with no Mn have a higher elongation than the other alloys.

4.2.2 The effect of Mn on the Strength Coefficient (K)

As cast samples

Figure 13(a) shows the relation between the material's strength coefficient and Mn content for as-cast test bars. In this case the solidification time has considerable effect on K. Heat treatment lowered K for the "SDAS 10 µm" samples and raised it for the "SDAS 48 µm" samples.



(a) As Cast | (b) HT

Figure 13 (a-b) The effect of Mn on the strength coefficient (K)

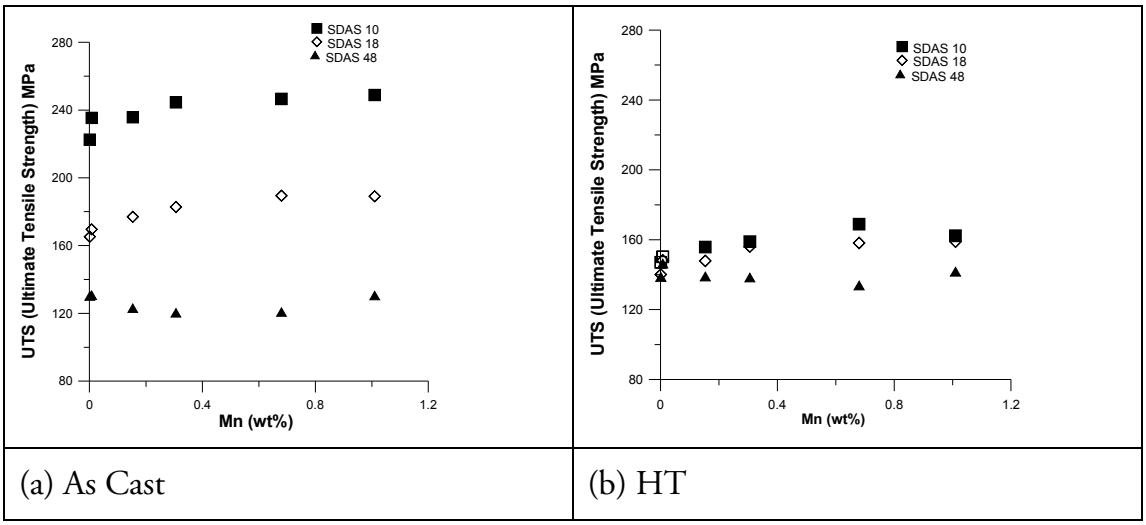
Heat treated samples

Figure 13(b) shows the relation between the material's strength coefficient and Mn content for heat-treated test bars. It looks like an optimal Mn content is between 0.4 and 0.8 percent. Mn shows a stronger effect on the as-cast samples.

4.2.3 The effect of Mn on UTS

As Cast

Figure 14(a) shows the effect of Mn on the ultimate tensile strength for as-cast bars. The graph shows an improvement in UTS with the increase of Mn for the "SDAS 10 µm" and "SDAS 18 µm" test bars. At 0.6% Mn the curve levels out and no further improvement is seen. For the "SDAS 48 µm" bars, Mn decreases UTS until 1% is added, when it improves slightly. Overall UTS is not raised.



(a) As Cast | (b) HT

Figure 14 (a-b) The effect of Mn on ultimate tensile strength (UTS).

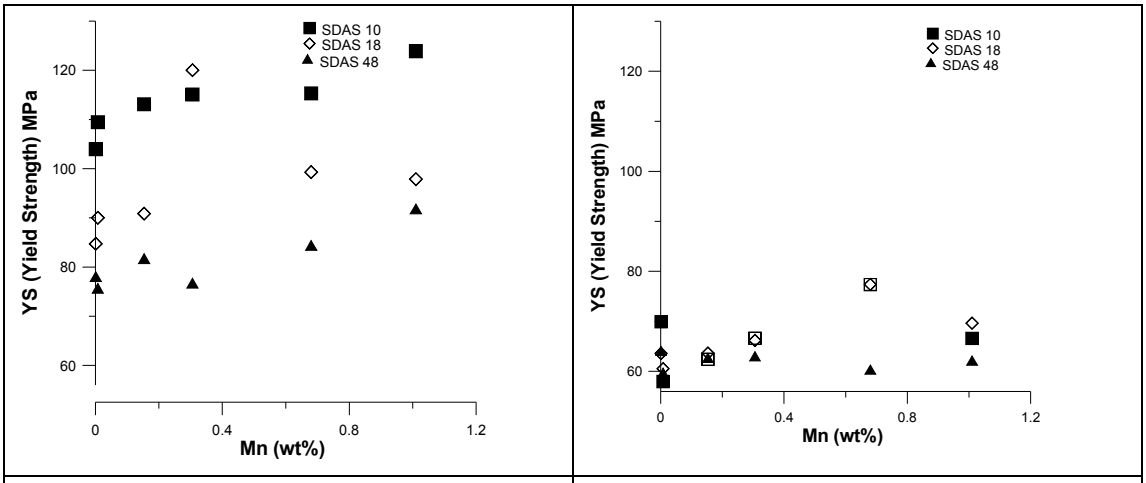
Heat treated

Figure 14(b) shows the effect of Mn on the ultimate tensile strength for heat treated test bars. Shorter solidification time gives higher UTS. It also increases with added Mn up to 0.7 %. Then it goes down. At slower solidification time Mn shows no improvement at all; UTS stays level.

4.2.4 The effect of Mn on Yield Strength

As cast

Figure 15(a) shows the optimal effect of Mn on yield strength (YS) for as-cast test bars. The graph shows a clear overall improvement on all test bars when Mn is increased.



(a) As Cast | (b) HT

Figure 15 (a-b). The effect of Mn on yield strength (YS).

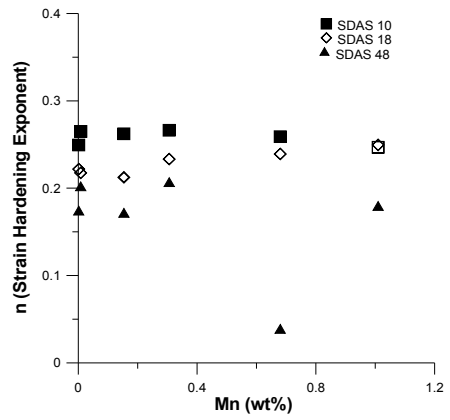
Heat treated

Figure 15(b) shows the effect of Mn on yield strength (YS) for heat treated test bars. Heat treatment lowers YS significantly for all test bars. Mn does not appear to affect YS; it stays level at about 65 MPa.

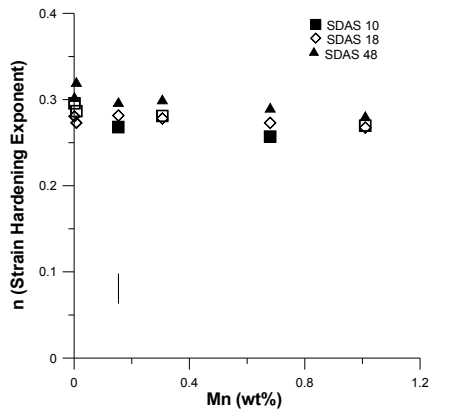
4.2.5 The effect of Mn on the strain hardening exponent

As cast

Figure 16(a) shows the effect of Mn on the strain hardening exponent of as-cast test bars. The greater SDAS have lower (n).



(a) As Cast



(b) HT

Figure 16 (a-b). The effect of Mn on the strain hardening exponent.

Heat treated

Figure 16(b) shows the relation between the strain hardening exponent (n) and Mn for heat treated test bars. Mn and the dendrite size have no significant effect at all to (n). The average of n is higher in the heat treated bars than in the as-cast ones.

5 Analysis

Fe in cast aluminum alloys has a detrimental effect on mechanical properties and is preferably kept as low as possible. In the absence of modifiers the iron forms large plate-like structures which hinder interdendritic feeding and cause porosity due to shrinkage. Also, cracks tend to start and spread through them. Mn is added to change the morphology of these intermetallic phases to less harmful ones. It is also added in some cases to reduce sticking to the die. Excessive amounts of Mn will cause sludge problems however.

5.1 Cooling Rate

The cooling rate and Mn content has the biggest impact on the formation of intermetallic phases. Fe needles were hard to discern and mostly were not observed at the highest cooling rate, even with 100x magnification. This is because they don't have time to grow during solidification. As the cooling rate decreases, more Fe needles are seen. The same observation was made about the Chinese script.

The cooling rate also affects the porosity level. The highest solidification rate showed smaller pores that were dispersed evenly throughout the material. There are less Fe needles in these alloys that would block feeding and also the finer structure allows a better flow of the melt which in turn does not allow for much pore formation. As cooling rate decreased the pores became larger and appeared in local concentrations. According to Campbell [16] lengthy cooling rates often result in shrinkage porosity which could be an explanation to why much larger pores were encountered in the slowly (0.03mm/s) cooled series. It is also possible that the large pores are formed when bifilms in the melt expand during cooling [16].

With the slowest cooling rate, there were many factors that could have caused differences in mechanical properties so it was more difficult to see the direct effect of Mn. Factors such as SDAS and pores caused premature breaks in many of the test bars.

5.2 Intermetallic phases

The first Chinese script phases were found in the MD test bars containing 0.3% Mn; and then only in the test bars cast at the slowest cooling rate. At values of 0.6% Mn and above the Chinese scripts were predominant. However, the harmful β-phase was never completely suppressed. Even in the MF test bars containing 1% Mn some Fe needles were still found; at a Mn/Fe ratio of 3. This is in contrast to an article written by A. G. Prigunova on the subject. He found that when the Mn/Fe ratio is greater than 1.2 for hypoeutectic alloys, only the α-phase forms [17]. These observations were made for alloys containing 0.7-1.3% Fe however, which may possibly account for the difference.

An increase in the size of needles and Chinese scripts was observed with greater Mn. Higher Mn resulted in a reduced amount of Fe needles but larger ones. Not enough values were used to make this observation statistically reliable however. There was also a greater fraction of intermetallic phases with higher Mn levels. Elongation decreased with the addition of Mn, which can be seen as a direct result of these higher fractions and larger needles. It is not clear why the needles are bigger with higher Mn and this was only found to be true on the "SDAS-18μm" and "SDAS-48μm" test bars (see figure 10), but it appears that too much Mn might counter the original purpose. This might not be so if all β-phases were suppressed. Perhaps the increases in Mn lead to an early formation of the metallic phase, as was discussed by Taylor [7]. When the intermetallic phases nucleate before the primary phase has solidified they are given more time and room to grow. Note that the Chinese scripts are only seen in the primary phases on the samples with high levels of Mn.

While ductility decreases with higher fractions of intermetallic phases, ultimate tensile strength and yield strength improve. It is clear then that Mn does not improve ductility, as it creates higher fractions of intermetallic phases. This is in accordance to the article written by Rheinfelden, where they state that Mn will lower ductility when its content exceeds 0.2% [12].

5.3 Heat treatment

5.3.1 The influence of Heat Treatment on mechanical properties

Heat treatment decreased the UTS, YS and K while it improved elongation and n. Heat treatment does not change the effect of Mn on the mechanical properties except for K. The as-cast graph shows an increase in K with higher levels of Mn whereas the heat treated graph stays level. A study made by Rheinfelden on an alloy called Castasil-37 showed that heat treatment does not change the effects of Mn on the mechanical properties. This is true for our samples also.

5.4 Pore fraction

This research verifies observations made by Carlos & Nestor in their thesis on pore concentration and appearance at different solidification rates [15]. They found that when Fe content was 0.3 % pore fraction decreased to 2 %, when adding 0.7 % Mn. This gives some support that Mn may decrease the pore fraction .When adding 0.3 % Mn at the same conditions as Carlos & Nestor the pore fraction was about 4 %. Twice the amount of pore fraction was observed with half the Mn content. One author in an investigation about engine block casting suggests a lot more strontium and low quantity of Mn in order to reduce micro porosity [21]. Mn may reduce shrinkage pores as well [11, 16].

A greater fraction of pores was found in the medium cooling rate than in the slowest cooling. However the largest pores were found in the slowest cooling (see appendix F). This indicates that cooling has the biggest impact on the size of the pores and Mn has the biggest impact on the fraction of pores. Perhaps a larger fraction is found in the medium cooling rate because the modification process takes time. More time allows a full modification. This would be true up to a point; for the highest cooling rate the Fe needles are few and small and do not need to be modified. This is supported by Campbell in his theory of how pores are not able to grow in high pressure die castings due to the small size of the SDAS [16].

The effect of porosity on mechanical properties was seen during the tensile tests. Approximately 40% of the test bars had pores on the fracture surface and can be assumed to have caused the break. Most of these test bars had solidified slowly and the pores were large. Premature breaks in pore areas caused a decrease in elongation of those samples.

6 Conclusion

Cooling

It is clear from the results in this research that the cooling rate has the biggest influence on the microstructure and mechanical properties; regardless of how much Mn or Fe is present in the alloy. At the highest cooling rate (3mm/s) the microstructure becomes very fine, and the Fe needles are small and nonexistent in most cases. Mn does not have time to modify the Fe and is therefore not needed when using this cooling rate. Also, fewer pores were encountered. With slower cooling rates the Mn content becomes more relevant.

Optimal Mn/Fe ratio

When it comes to the optimal Mn/Fe ratio, there are different ways to achieve the best ratio depending on which properties are looked at. Ultimate tensile strength and yield strength show best values at 0.6% Mn, after that it levels out. In order to get better elongation values however, it is best to use 1% Mn as elongation showed low values at 0.6% Mn and improved thereafter. According to literature however, one should not have more than 0.8% Mn in order to ease machinability. 1% Mn (3:1 ratio) may cause problems in that aspect.

Fe content

Overall, the alloys without Mn showed better qualities, especially elongation. UTS and YS and K increased but not substantially, whereas elongation showed a great difference (6-7%). Also, there was little change observed when going from alloy A to B, where iron was only present in B. This indicates that with 0.3% Fe it is better not to add Mn when trying to optimize both ductility and strength.

Porosity

Pores were found in the fracture surface of approximately 40% of the test bars and were concluded to be a direct cause of the break. The pore fraction and size need to be controlled in order to increase the strength of an alloy. The concentration of pores in the alloys can be caused by a number of different factors, which were discussed earlier. However, the cooling rate once again has the biggest influence. The fastest cooling rates lead to less fractions and smaller pores.

Mn caused an increase in the size of the pores but resulted in a lower fraction. Overall the addition of Mn was not beneficial to our alloy containing 0.3% Fe

Heat treatment

The influence of Mn on mechanical properties is not affected by heat treatment.

Further investigations

0.3% Fe is an acceptable level. Further investigations on an alloy with 0.6% would be interesting, to see if iron can be modified to obtain the same mechanical properties that alloys with 0.3% Fe has. Electromagnetic filtration is one method of decreasing the Fe content. If modification were successful in these alloys, it would be a cheaper alternative. It would be interesting to compare one filtered casting with one unfiltered casting and see what influence it has on pore fraction for instance (bifilm problems). Another fascinating investigation would be to do a pre-heat treatment similar to the one discussed by Zhang Lei [13]. Some changes in the foundry would be of interest, if the pouring technique and the control of vapor sources can be improved.

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Designations for cast aluminum alloys

The designations for cast aluminum alloys and ingots consist of four digits. The first digit indicates the major alloy group, as follows.

1xx.x – Aluminum (99 percent minimum)
2xx.x – Aluminum-copper
3xx.x – Aluminum-silicon, with copper and/or magnesium.
4xx.x – Aluminum-silicon.
5xx.x – Aluminum-magnesium.
6xx.x – Unused series.
7xx.x – Aluminum-zinc.
8xx.x – Aluminum-tin.

In the 1xx.x series, the second and third digits indicate the minimum aluminum content, as I wrought aluminum. For the other series, the second and third digits have no numerical significance. The fourth digit (to the right of the decimal point) indicates product form. [3]

Silafont-09 Properties

Chemical composition (wt %)

Si – 9.5-9.6
Fe – 0.4
Cu – 0.02
Mn – 0.4
Mg – 0.05
Zn – 0.10
Ti – 0.10

Mechanical properties

Yield Strength: 140-180MPa
Ultimate Tensile Strength: 240-280MPa
Elongation: 5-10%
Brinell Hardness: 60-80
Fatigue Resistance: 60-70Mpa

Alloy compositions

Al	Si	Mg	Cu	Fe	Mn	Ti	Zn	Ni	Cr	Sr
MA	9,52	0,0047	0,0036	0,096	0,0012	0,0038	0,0038	0,0023	0,0011	200ppm
MB	9,13	0,0034	0,0026	0,32	0,0078	0,0014	0,0065	0,0018	0,0005	200ppm
MC	9,7	0,0022	0,0031	0,31	0,1534	0,0032	0,0033	0,0049	0,0017	170ppm
MD	9,27	0,0007	0,0031	0,37	0,306	0,0049	0,0049	0,0069	0,0014	170ppm
ME	9,1	0,0012	0,0028	0,37	0,68	0,0022	0,0029	0,0076	0,0012	160ppm
MF	9,2	0,001	0,0026	0,38	1,01	0,0013	0,0043	0,0028	0,0005	190ppm

Nomenclature

Example: position

A 16 M C 1 2 HT

1 A : aluminum

2 16 : project number

3 M : manganese

4 C : 0.1 % Fe, 0 % Mn

5 1: solidification rate 3mm/s

6 2 : sample number

7 HT: heat treated

Position 4 can take on values A-F depending on how much of Fe and Mn is added

A : 0.1 % Fe, 0 % Mn

B : 0.3 % Fe, 0 % Mn

C : 0.3 % Fe, 0.15 % Mn

D : 0.3 % Fe, 0.3 % Mn

E : 0.3 % Fe, 0.6 % Mn

F : 0.3 % Fe, 1.0 % Mn

Position 5 can take on three different values depending on the solidification rate.

1 : 3 mm/s (pressure die casting)

	Si	Fe	Mn	Mn/Fe	UTS	YS	E	eb	e (%)	ep	n	k	Q	SDAS	ß-needles	Chinese signs
A16MA11	9,52	0,10	0,00		223	104	83417	0,16	16,2	0,15	0,24	469,87	441,95	8,51		
A16MA12	9,52	0,10	0,00		222	102	95160	0,16	16,0	0,15	0,25	494,16	451,57			
A16MA13	9,52	0,10	0,00		216	102	96201	0,10	9,6	0,09	0,25	472,68	396,20			
A16MA21	9,52	0,10	0,00		162	82	90696	0,20	19,7	0,18	0,22	310,46	317,34	19,99		
A16MA22	9,52	0,10	0,00		162	80	110741	0,21	20,8	0,19	0,22	316,25	323,34			
A16MA23	9,52	0,10	0,00		165	85	77209	0,17	17,4	0,16	0,21	313,44	315,46			
A16MA31	9,52	0,10	0,00		127	77	85282	0,09	8,9	0,08	0,17	221,46	209,13	50,70		
A16MA32	9,52	0,10	0,00		124	78	86070	0,06	5,6	0,05	0,17	224,53	189,82			
A16MA33	9,52	0,10	0,00		129	75	93445	0,11	10,5	0,10	0,17	225,47	219,15			
MA11HT	9,52	0,10	0,00		147	70	96662	0,31	30,8	0,27	0,22	268,26	300,17			
MA12HT	9,52	0,10	0,00						0,0							
MA13HT	9,52	0,10	0,00		147	55	118335	0,30	29,7	0,26	0,30	337,56	338,01			
MA21HT	9,52	0,10	0,00		139	60	49636	0,28	27,8	0,24	0,26	294,53	302,48			
MA22HT	9,52	0,10	0,00		140	56	67895	0,29	29,5	0,26	0,28	314,55	317,58			
MA23HT	9,52	0,10	0,00		140	64	96959	0,30	29,8	0,26	0,24	276,98	296,74			
MA31HT	9,52	0,10	0,00		138	64	136197	0,09	9,1	0,09	0,26	317,75	256,81			
MA32HT	9,52	0,10	0,00		133	55	34640	0,06	6,3	0,06	0,30	363,24	243,75			
MA33HT	9,52	0,10	0,00		127	54	70871	0,05	5,0	0,05	0,29	340,10	218,76			

	Si	Fe	Mn	Mn/Fe	UTS	YS	E	eb	e (%)	ep	n	k	Q	SDAS	ß-needles	Chinese signs
A16MB11	9,13	0,32	0,01		235	109	115212	0,15	14,8	0,14	0,24	494,05	459,08	8,70		
A16MB12	9,13	0,32	0,01		207	100	147061	0,06	5,5	0,05	0,26	514,50	355,62			
A16MB13	9,13	0,32	0,01		220	104	108693	0,08	7,9	0,07	0,25	490,02	390,11			
A16MB21	9,13	0,32	0,01		170	90	66019	0,11	10,8	0,10	0,21	322,59	298,75	16,60		
A16MB22	9,13	0,32	0,01		168	86	72577	0,17	17,4	0,16	0,22	326,56	325,01			
A16MB23	9,13	0,32	0,01		168	85	112022	0,17	17,1	0,16	0,22	326,87	324,23			
A16MB31	9,13	0,32	0,01		130	69	95494	0,16	16,0	0,15	0,20	243,60	243,67	46,36	33,47	
A16MB32	9,13	0,32	0,01		129	75	120580	0,09	9,2	0,09	0,18	235,81	217,79			
A16MB33	9,13	0,32	0,01		127	70	118935	0,06	6,5	0,06	0,20	245,65	205,30			
MB11HT	9,13	0,32	0,01		140	58	71705	0,26	26,0	0,23	0,27	310,28	309,33			
MB12HT	9,13	0,32	0,01		145	56	107514	0,31	31,3	0,27	0,29	331,37	335,14			
MB13HT	9,13	0,32	0,01		150	56	80483	0,28	27,5	0,24	0,29	337,00	336,67			
MB21HT	9,13	0,32	0,01		148	61	42160	0,25	25,3	0,22	0,27	323,50	322,44			
MB22HT	9,13	0,32	0,01		147	61	56692	0,27	26,8	0,23	0,27	323,16	324,04			
MB23HT	9,13	0,32	0,01		134	57	85653	0,07	7,3	0,07	0,28	313,34	239,61			
MB31HT	9,13	0,32	0,01		145	56	70792	0,09	8,5	0,08	0,30	366,96	277,53			
MB32HT	9,13	0,32	0,01		142	52	133543	0,07	7,1	0,07	0,32	385,93	270,52			
MB33HT	9,13	0,32	0,01		146	59	78626	0,10	10,2	0,10	0,28	340,29	279,54			

	Si	Fe	Mn	Mn/Fe	UTS	YS	E	eb	e (%)	ep	n	k	Q	SDAS	ß-needles	Chinese signs
A16MC11	9,70	0,31	0,15	0,49	230	106	79224	0,09	8,5	0,08	0,26	532,71	421,51	9,35		
A16MC12	9,70	0,31	0,15	0,49					0,0							
A16MC13	9,70	0,31	0,15	0,49	236	113	70660	0,14	14,2	0,13	0,24	493,18	455,25			
A16MC21	9,70	0,31	0,15	0,49	174	91	75602	0,16	15,7	0,14	0,20	323,51	323,66	18,17	7,99	
A16MC22	9,70	0,31	0,15	0,49	167	88	85665	0,10	9,5	0,09	0,21	320,21	289,05			
A16MC23	9,70	0,31	0,15	0,49	177	91	70250	0,11	10,6	0,10	0,21	341,89	312,72			
A16MC31	9,70	0,31	0,15	0,49	122	78	66091	0,04	3,8	0,04	0,17	229,26	174,30	40,10	24,10	
A16MC32	9,70	0,31	0,15	0,49	122	75	95973	0,07	7,1	0,07	0,17	216,85	193,93			
A16MC33	9,70	0,31	0,15	0,49	113	81	105776	0,02	1,7	0,02	0,16	218,35	131,62			
MC11HT	9,70	0,31	0,15	0,49	152	60	74273	0,27	27,3	0,24	0,26	307,03	320,85			
MC12HT	9,70	0,31	0,15	0,49	156	62	69144	0,27	27,4	0,24	0,25	307,87	325,77			
MC13HT	9,70	0,31	0,15	0,49	153	62	66470	0,25	25,3	0,22	0,27	330,84	331,17			
MC21HT	9,70	0,31	0,15	0,49	146	143	65887	0,15	15,0	0,14	0,02	162,55	220,01			
MC22HT	9,70	0,31	0,15	0,49	148	59	122462	0,23	22,7	0,20	0,28	335,85	323,59			
MC23HT	9,70	0,31	0,15	0,49	146	64	43310	0,24	24,3	0,21	0,26	309,03	310,68			
MC31HT	9,70	0,31	0,15	0,49	128	62	65567	0,07	6,7	0,06	0,24	278,64	217,04			
MC32HT	9,70	0,31	0,15	0,49	138	55	46632	0,10	10,3	0,10	0,29	337,99	272,03			
MC33HT	9,70	0,31	0,15	0,49	131	52	41791	0,08	7,5	0,07	0,30	333,18	242,77			

	Si	Fe	Mn	Mn/Fe	UTS	YS	E	eb	e (%)	ep	n	k	Q	SDAS	ß-needles	Chinese signs
A16MD11	9,27	0,37	0,31	0,80	240	108	96319	0,08	7,6	0,07	0,27	565,81	432,24	9,70		
A16MD12	9,27	0,37	0,31	0,80	245	111	100928	0,13	13,3	0,12	0,26	562,66	489,15			
A16MD13	9,27	0,37	0,31	0,80	243	115	61850	0,14	13,6	0,12	0,24	514,71	467,89			
A16MD21	9,27	0,37	0,31	0,80	183	120	80116	0,06	6,1	0,06	0,15	307,08	275,58	17,36	10,32	
A16MD22	9,27	0,37	0,31	0,80	181	89	95930	0,11	11,0	0,10	0,23	382,35	334,92			
A16MD23	9,27	0,37	0,31	0,80	179	93	76418	0,09	8,6	0,08	0,22	360,33	309,20			
									0,0							
A16MD31	9,27	0,37	0,31	0,80	118	76	84002	0,05	5,1	0,05	0,17	225,92	180,30	49,60	34,16	3536,69
A16MD32	9,27	0,37	0,31	0,80	102	73	76038	0,01	1,5	0,01	0,18	223,06	114,06			
A16MD33	9,27	0,37	0,31	0,80	119	76	118151	0,03	2,7	0,03	0,21	272,69	165,76			
MD11HT	9,27	0,37	0,31	0,80	152	61	76077	0,26	25,8	0,23	0,28	355,62	345,07			
MD12HT	9,27	0,37	0,31	0,80	159	65	81464	0,29	29,2	0,25	0,27	355,13	358,63			
MD13HT	9,27	0,37	0,31	0,80	154	67	37355	0,25	25,4	0,22	0,26	328,12	330,45			
MD21HT	9,27	0,37	0,31	0,80	152	63	78730	0,22	22,3	0,20	0,27	344,47	331,32			
MD22HT	9,27	0,37	0,31	0,80	154	66	60493	0,22	21,7	0,19	0,26	330,73	324,29			
MD23HT	9,27	0,37	0,31	0,80	156	63	68619	0,21	21,3	0,19	0,28	355,54	338,15			
MD31HT	9,27	0,37	0,31	0,80	136	56	68306	0,05	5,2	0,05	0,30	364,61	236,75			
MD32HT	9,27	0,37	0,31	0,80	138	63	56369	0,05	4,6	0,04	0,28	366,76	229,46			
MD33HT	9,27	0,37	0,31	0,80	136	58	114214	0,05	4,8	0,05	0,29	354,96	229,39			

A16ME11	9,10	0,37	0,68	1,83	247	112	116044	0,09	9,4	0,09	0,26	562,83	458,62	11,84	23,26	
A16ME12	9,10	0,37	0,68	1,83	224	115	104878	0,03	3,5	0,03	0,26	586,65	342,27			
A16ME13	9,10	0,37	0,68	1,83	245	115	89175	0,11	10,9	0,10	0,25	543,15	463,45			
A16ME21	9,10	0,37	0,68	1,83	188	99	66996	0,08	8,3	0,08	0,22	403,10	330,84	19,40	12,39	1224,696
A16ME22	9,10	0,37	0,68	1,83	186	95	98174	0,10	9,8	0,09	0,23	397,86	338,93			
A16ME23	9,10	0,37	0,68	1,83	189	94	99053	0,10	9,6	0,09	0,24	422,80	350,76			
A16ME31	9,10	0,37	0,68	1,83	117	80	74490	0,04	3,8	0,04	0,17	226,69	168,77	50,50	147,73	4970,695363
A16ME32	9,10	0,37	0,68	1,83	120	80	84699	0,05	5,4	0,05	0,17	228,07	185,46			
A16ME33	9,10	0,37	0,68	1,83	113	84	165712	0,01	1,2	0,01	0,17	248,37	119,84			
ME11HT	9,10	0,37	0,68	1,83	169	77	49938	0,21	20,9	0,19	0,25	359,02	351,33			
ME12HT	9,10	0,37	0,68	1,83	167	74	70629	0,21	20,6	0,18	0,25	359,33	349,22			
ME13HT	9,10	0,37	0,68	1,83	169	74	71050	0,12	12,0	0,11	0,26	364,03	320,62			
ME21HT	9,10	0,37	0,68	1,83	158	70	117314	0,06	6,0	0,06	0,27	386,24	274,76			
ME22HT	9,10	0,37	0,68	1,83	154	77	80869	0,13	12,8	0,12	0,23	325,04	294,08			
ME23HT	9,10	0,37	0,68	1,83	157	71	46554	0,12	11,5	0,11	0,26	375,71	311,20			
ME31HT	9,10	0,37	0,68	1,83	122	58	91243	0,05	5,3	0,05	0,29	352,32	221,55			
ME32HT	9,10	0,37	0,68	1,83	133	57	64195	0,05	5,5	0,05	0,29	359,95	236,27			
ME33HT	9,10	0,37	0,68	1,83	124	60	45852	0,04	3,8	0,04	0,26	310,42	191,90			

A16MF11	9,20	0,38	1,01	2,66	249	117	88929	0,10	10,3	0,10	0,25	544,27	462,11	9,40	18,20	
A16MF12	9,20	0,38	1,01	2,66	240	115	93955	0,06	5,9	0,05	0,25	545,57	400,80			
A16MF13	9,20	0,38	1,01	2,66	246	124	67680	0,13	12,7	0,12	0,23	501,17	459,60			
A16MF21	9,20	0,38	1,01	2,66	181	92	106079	0,04	4,2	0,04	0,25	440,30	285,75	18,13		2182,00
A16MF22	9,20	0,38	1,01	2,66	187	97	87096	0,07	7,4	0,07	0,24	421,91	328,46			
A16MF23	9,20	0,38	1,01	2,66	189	98	73364	0,09	9,2	0,09	0,23	405,80	340,30			
A16MF31	9,20	0,38	1,01	2,66	130	91	63970	0,02	2,1	0,02	0,15	240,92	157,42	48,22		39689,87
A16MF32	9,20	0,38	1,01	2,66	109	76	79655	0,03	3,3	0,03	0,18	231,36	156,07			
A16MF33	9,20	0,38	1,01	2,66	123	79	76729	0,03	3,0	0,03	0,17	226,68	165,37			
MF11HT	9,20	0,38	1,01	2,66	145	67	80484	0,08	8,2	0,08	0,26	346,99	269,15			
MF12HT	9,20	0,38	1,01	2,66	159	66	104750	0,24	23,9	0,21	0,26	338,09	338,60			
MF13HT	9,20	0,38	1,01	2,66	162	67	40254	0,23	23,4	0,21	0,27	361,06	352,15			
MF21HT	9,20	0,38	1,01	2,66	159	70	52872	0,19	19,4	0,17	0,26	345,06	330,16			
MF22HT	9,20	0,38	1,01	2,66	158	69	47753	0,20	20,1	0,18	0,26	354,89	335,60			
MF23HT	9,20	0,38	1,01	2,66	156	67	55452	0,20	20,4	0,18	0,27	356,64	336,19			
MF31HT	9,20	0,38	1,01	2,66	124	62	128398	0,03	3,2	0,03	0,26	312,89	186,33			
MF32HT	9,20	0,38	1,01	2,66	131	57	59033	0,09	8,9	0,08	0,28	329,66	253,61			
MF33HT	9,20	0,38	1,01	2,66	141	61	55741	0,07	7,2	0,07	0,26	323,71	248,82			

Approximated Pore observation in samples

Alloy	fraction %	comments
A16MA11-13	0,1	very small
A16MB11-13	0,2	very small, small
A16MC11-13	0,4	very small, small
A16MD11-13	0,4	small, dispersed
A16ME11-13	0,2	small, dispersed
A16MF11-13	0,2	small, dispersed
A16MA21-23	2	large, dispersed
A16MB21-23	2	large, nonsym.dispersed
A16MC21-23	4	large, nonsym.dispersed
A16MD21-23	3	large & small
A16ME21-23	2,5	large & small
A16MF21-23	2	large & small
A16MA31-33	0,4	extra large, large& small
A16MB31-33	1	extra large, large& small
A16MC31-33	1	extra large, large& small
A16MD31-33	1	extra large, large& small
A16ME31-33	1	extra large, large& small
A16MF31-33	0,5	extra large, large& small