EFFECT OF ALLOYING ELEMENTS (MAGNESIUM AND COPPER) ON HOT CRACKING SUSCEPTIBILITY OF AlSi7MgCu-ALLOYS

Salar Bozorgi[1], Katharina Haberl[1], Christian Kneissl[2], Thomas Pabel[2], Peter Schumacher[1,2]

[1]Chair of Casting Research, Metallurgy Department, University of Leoben, Franz-Josef-Str. 18, 8700 Leoben, Austria
[2]Austrian Foundry Research Institute, Parkstr. 21, 8700 Leoben, Austria

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Abstract

Hot cracking during solidification can be a serious problem in aluminium casting alloys under certain conditions. This feature is well known but still insufficiently investigated in shape casting. This study gives a brief overview of the factors influencing hot cracking during shape casting. Five different AlSi7MgCu-alloys with varying Mg and Cu contents were examined. Theoretical models including the cracking susceptibility coefficient (CSC) from Clyne and Davies have been considered. Thermodynamic calculations of the behaviour of the fraction solid during solidification have been compared to an experiment based hot cracking indexing (HCI) method. Scanning electron microscopy (SEM) was used to compare existing microstructure and precipitated thermodynamic phases. Furthermore, SEM was used to investigate crack surfaces initiated by a dog bone shaped mold during casting. A good correlation between theoretical models and the experimental hot cracking index method was observed.

Introduction

AlSi7MgCu-alloys find wide application in many castings especially in the automotive industry. Complex thin walled components, such as cylinder heads, can be achieved. One serious problem in shape casting can be hot cracks which are fundamentally influencing the quality characteristics of a casting. In general the hot cracking susceptibility of AlSi-alloys is lower than in other Al-alloys such as AlZn, AlMg, or AlZnMg(Cu) [1-3]. However, various amounts of alloying elements can affect the hot cracking susceptibility of AlSi-alloys.

In grain refined alloys hot cracks occur when insufficiently feeding by two phase flow and liquid flow between grains cannot accommodate the deformation caused by a hindered shrinkage [4]. At the point of rigidity bridges are formed between grains which do not permit further two phase flow. Subsequent micro feeding between grains cannot compensate shrinkage, stresses and strains occur, so that hot cracks can be generated in the final stage of solidification [5-7]. These cracks remain in the solidified casting. However, the exact mechanism nucleating a hot crack is still under discussion.

Theoretical Background

<u>Influencing Factors.</u> The most important factor on hot cracking is the chemical composition affecting freezing range, grain size, fraction of eutectic and segregation for a given casting process.

Freezing Range. In general as the freezing range increases the hot cracking susceptibility also increases. Depending on cooling conditions, a long freezing range leads to the formation of complex dendrites which interlock at relatively low fraction solid to form rigid bridges. Subsequently, feeding at the late stages of solidification is greatly hindered. Because pure metals and eutectic alloys have little to no freezing range, they show no hot cracking susceptibility [7-9]. The chemical composition is the main influencing factor on the freezing range. Impurities and their segregations which increase the freezing range are deleterious [9]. Furthermore, the final freezing range, the so-called terminal freezing range (TFR), is of major importance. A large TFR is objectionable; it causes a higher risk of hot cracks in the last stage of solidification [9]. If in an eutectic system a large amount of dendrites is formed already well above the solidus (i.e. at high temperature), the alloy possesses a high strength during final solidification of the remaining liquid, resisting contractional stresses. For alloys close to eutectic composition, large amounts of liquid freeze isothermally at the eutectic temperature (i.e. at low temperature) and shrinkage stresses are kept small [9]. It has been suggested by Djurdjewic et al. [10] to define TFR in temperature intervals of mass fraction solid 88-98%, 85-95% or others. In this study the solid fraction for TFR is defined as 95-99.5%. The very last percentage is neglected because of susceptibility to errors [10].

Grain Size. A fine grain size causes better feeding and uniform distribution of eutectic phases. When eutectic is present at grain boundaries, it has the maximum effect on permitting free movement of grains to accommodate contraction of the casting by two phase flow [11]. Bishop [12] and Lees [13] considered the effect of grains on hot tearing. They suggested that coarse grains result locally in a high thermal concentration of strain per grain boundary and, therefore, to hot cracking. In contrast a fine grain size results in a decrease in strain concentration accompanied by a decrease in hot cracking tendency [12,13]. However, the deformation of a granular structure should be considered as a movement within a network of grains and not of individual grains. The most common way to obtain fine grains is the addition of grain refiner or to increase the cooling rate. In this study the grain size was kept constant for die cast samples (~ 250 μm) and sand cast samples (~ 350 μm).

Fraction of Eutectic Phase. A high fraction of eutectic phase in the microstructure and an eutectic phase with sufficient wettability results in a decreasing susceptibility for hot cracking. The eutectic surrounds the entire primary crystalline grains. Furthermore, a sufficient eutectic film between grains eases the movement of the granular system. If contraction and stresses occur, developing cracks are healed by backfilling [7,8]. It is important to note for Si-containing alloys that Si exhibits a volumetric expansion during solidification and thus helps micro feeding. Small amounts of impurities which exist in the melt can form low melting eutectics. If more strain is imposed the tendency towards hot cracking increases markedly [12]. The reason for this is the weak bridging between dendrites. When tensile stresses occur weak bridges degrade, a hot crack may form between the grains [14,15].

Theoretical Models. There are various theoretical models for the calculation of the hot cracking tendencies. The most commonly used is the cracking susceptibility coefficient (CSC) model from Clyne and Davies for shape casting. [16]. However, the model describes only the material properties based on Gulliver-Scheil assumption and not the casting process condition. Other models are e.g. from Katgerman [17], Feurer [18] or Rappaz et al. [19]. However, all the mentioned models are not always applicable to different casting processes such as continuous, direct, chill, shape casting or welding. The CSC model correlates the susceptibility-composition relationship based on the consideration of the time during which processes related to crack production may take place and the structure is most vulnerable to cracking (critical time interval during solidification). The CSC is defined as = t_V/t_R; t_V is the vulnerable time period and is calculated as the time difference between mass fraction of liquid 10% and mass fraction of liquid 1%. t_R is the time available for stress relief processes and is calculated as the time difference between mass fraction of liquid 60% and mass fraction of liquid 10%.

A comprehensive study on the hot cracking susceptibility was performed to compare theoretical and practical techniques. Therefore CSC was examined semi-empirical and HCI was examined experimental. In this present work five different AlSi7MgCu-alloys with varying Mg and Cu content were investigated.

Experimental

Five different AlSi7MgCu-alloys with varying Mg and Cu-content, AlSi7Mg0.1Cu0.05, AlSi7Mg0.1Cu0.5, AlSi7Mg0.3Cu0.05, AlSi7Mg0.6Cu0.05, and AlSi7Mg0.6Cu0.5, were examined by using subsequently mentioned methods. The experimental tests were performed in sand and in die casting to evaluate the effect of the casting process.

TFR. The TFR was calculated by the software ThermoCalc Classic (TCC) (Stockholm, Sweden), the database used was TTAl5. For simulation of the solidification process existing phases and their fraction at the different temperatures were calculated for non equilibrium using Gulliver-Scheil. For the forecast of precipitated phases in the as-cast microstructure at room temperature equilibrium conditions were chosen.

CSC. CSC was calculated semi-empirically using TCC for the evaluation of temperatures and mass fractions combined with practical thermal analysis in a permanent die mold (die temperature 250°C) and a sand mold for evaluation of associated times for t_V and t_R. The thermocouple used for thermal analysis was a type K-element.

HCI. For HCI examination experimental casts in dog bone shaped die mold (die temperature 250°C) and sand mold were performed. The molds were identical in shape apart from the gating system. Fig. 1 shows the dog bone shaped sand casting. HCI is defined as = ∑(NOC*WF)/NOF; NOC is the number of cracks, WF is the weighting factor, depending on the observed level of hot cracking (see Fig. 2) and NOF is the number of castings [11,20,21].

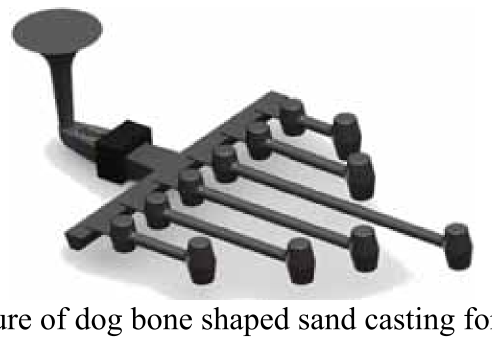

Figure 1. 3D-picture of dog bone shaped sand casting for HCI evaluation.

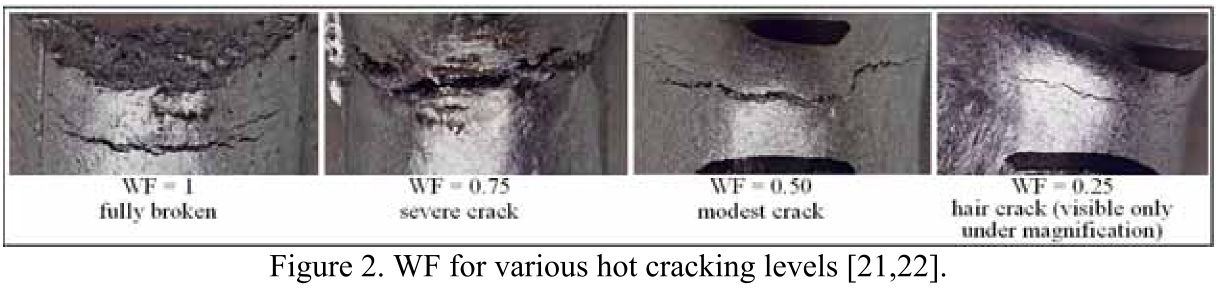

Figure 2. WF for various hot cracking levels [21,22].

The HCI can be defined as follows [22]:

- < 0.5 no hot cracking susceptibility
- 0,5 – 1.25 small cracking susceptibility
- 1.25 – 2.25 moderate cracking susceptibility
- 2.25 – 3.5 high hot cracking susceptibility
- > 3.5 very high hot cracking susceptibility

Microscopy. SEM examination was performed at 20 kV in BSD-mode to compare the as-cast microstructure with results from TCC and to investigate fracture surfaces.

Results

As-Cast Microstructure. Existing phases in the as-cast microstructure of various alloys were calculated by TCC (equilibrium conditions) and are shown in Fig. 3. Microstructure examination with SEM confirmed the theoretical predicted results. Alloy AlSi7Mg0.6Cu0.5 is given as an example in Fig. 4 to compare forecast phases by TCC and detected phases by SEM. Qualitatively, it is apparent from 50 EDX point analysis that in the sand mold a higher fraction of Mg_2Si can be found.

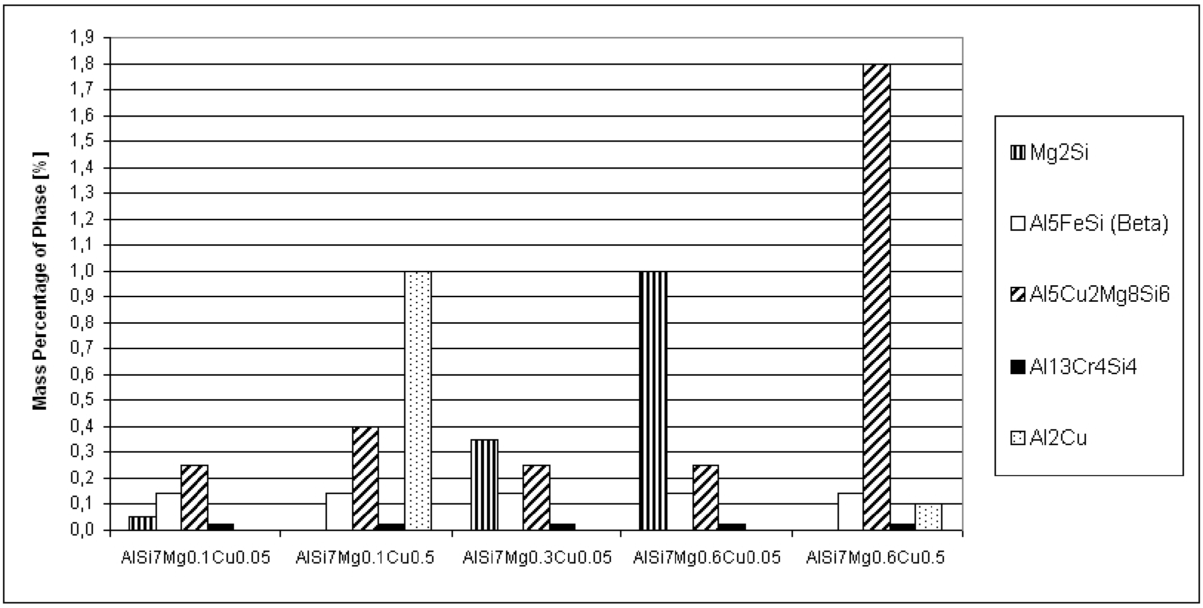

Figure 3. As-cast phases at room temperature, calculated by TCC in equilibrium.

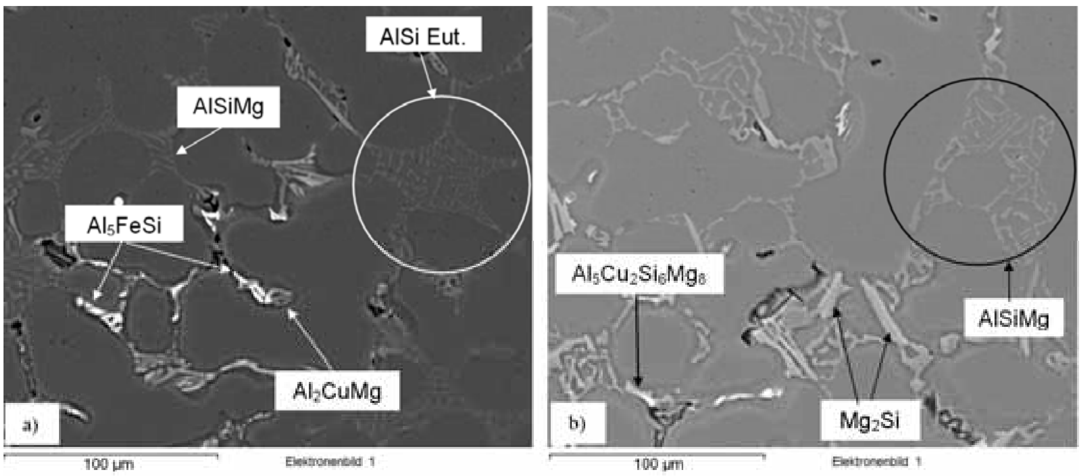

Figure 4. SEM, BSD, AlSi7Mg0.6Cu0.5, as-cast phases, (a) die mold, (b) sand mold.

Crack Surfaces. Crack surfaces initiated during casting of the HCI-samples in the dog bone shaped die were investigated by SEM. Samples with a small hot cracking level, i.e. samples not completely separated by a crack, were mechanically opened to subsequently observe the crack surface. Fig. 5 shows three SEM pictures of various hot cracking levels. SEM results indicate that at areas next to hot cracks no or insufficient eutectic phase exists. Furthermore, detailed SEM investigation of the fracture surfaces revealed no presence of bifilms as these may act as crack initiation sides within interdendritic liquid.

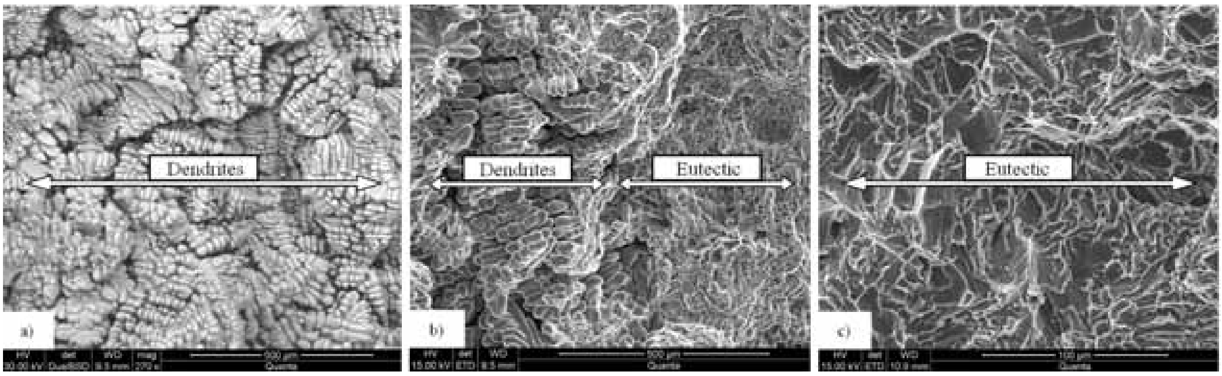

Figure 5. SEM, fracture surfaces, (a) dendrites in fully broken sample, WF=1, (b) dendrites and eutectic phase in sample with modest crack, WF=0.5 - mechanically opened, (c) eutectic in sample with hair crack, WF=0.25 - mechanically opened.

TFR. Table 1 shows the TFR of all alloys. It is evident that the Cu-content has the dominating influence on TFR over that of Mg-content. Firstly, a high Cu-content results in a large TFR. Secondly, a low Mg-content results also in large TFR. Hence, the largest TFR is obtained in the alloy AlSi7Mg0.1Cu0.5 (see Fig. 6), the smallest TFR is obtained in the alloy AlSi7Mg0.6Cu0.05 (see Fig. 7).

Table 1. TFR of evaluated alloys, calculated with TCC.

Alloy	TFR [°C]
AlSi7Mg0.1Cu0.5	46.0
AlSi7Mg0.6Cu0.5	27.0
AlSi7Mg0.1Cu0.05	17.0
AlSi7Mg0.3Cu0.05	9.5
AlSi7Mg0.6Cu0.05	4.0

CSC. Table 2 shows the CSC of three evaluated alloys. Again Cu has the dominant influence on the CSC. A high Cu-content results in a high CSC, a low Mg-content results also in a high CSC. Furthermore, the CSC results show that the CSC is much lower in sand casting than in die casting. The reason for this is a longer solidification time in sand casting and the larger amount of eutectic present which may induce a healing process for cracks.

Table 2. CSC of evaluated alloys.

Alloy	CSC [-]	
	Die Mold	Sand Mold
AlSi7Mg0.1Cu0,5	7.3	0.69
AlSi7Mg0.6Cu0,5	4.5	0.36
AlSi7Mg0.1Cu0.05	3.7	0.33

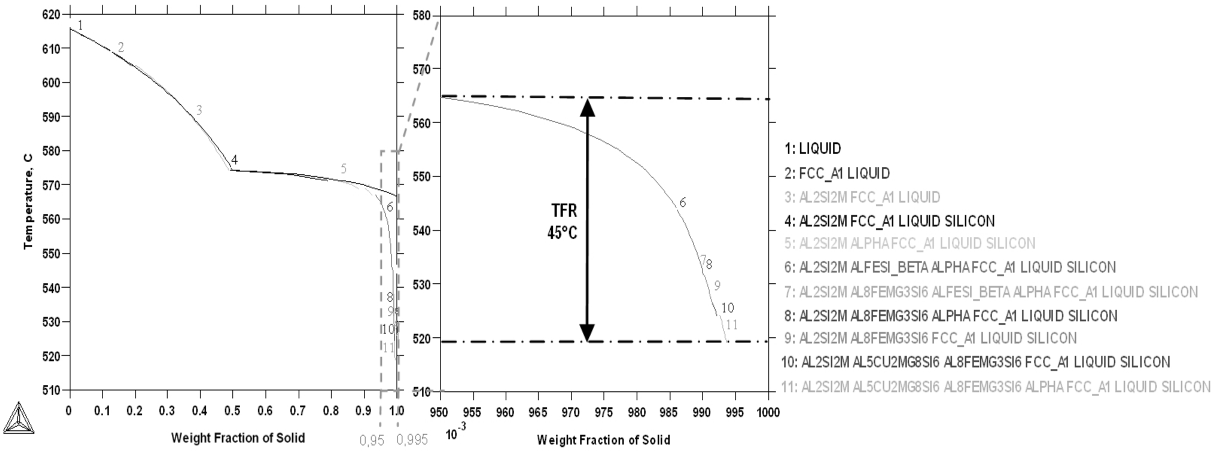

Figure 6. TCC, calculation of TFR (45°C), AlSi7Mg0.1Cu0.5.

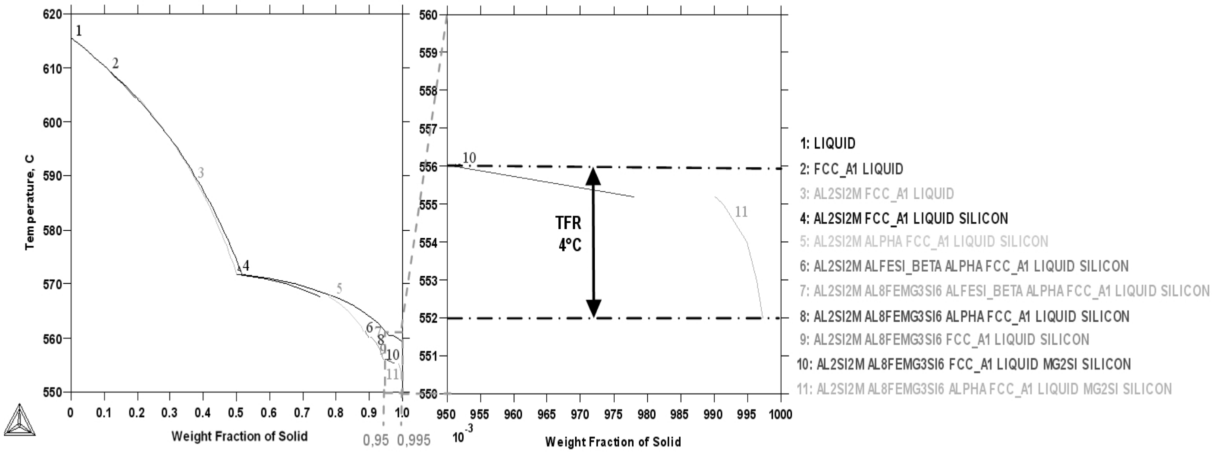

Figure 7. TCC, calculation of TFR (4°C), AlSi7Mg0.6Cu0.05.

HCI. Table 3 shows the HCI and subsequent resulting hot cracking susceptibility. For every alloy five hot cracking samples were investigated (NOF=5). Again Cu has a dominant effect on HCI. A high Cu-content results in a high HCI, a low Mg-content results also in a high HCI. Furthermore, all hot cracking susceptibilities for alloys in sand casting are negligible.

Table 3. HCI and hot cracking susceptibility of evaluated alloys.

Alloy	HCI [-] Die Mold	Hot Cracking Susceptibility	HCI [-] Sand Mold	Hot Cracking Susceptibility
AlSi7Mg0.1Cu0.5	0.8	small susceptibility	0.01	no susceptibility
AlSi7Mg0.6Cu0.5	0.6	small susceptibility	0.01	no susceptibility
AlSi7Mg0.1Cu0.05	0.3	no susceptibility	0.01	no susceptibility
AlSi7Mg0.3Cu0.05	0.22	no susceptibility	-	no susceptibility
AlSi7Mg0.6Cu0.05	0.01	no susceptibility	-	no susceptibility

Summary of Results. Figure 8 shows in a summary of results the theoretical models and the experimental hot cracking index method for different AlSi7MgCu-alloys. On the left y-axis TFR values are plotted. On the right y-axis CSC and HCI values are plotted, the HCI values are multiplied by 10 so that it was possible to show both measurement values on one axis.

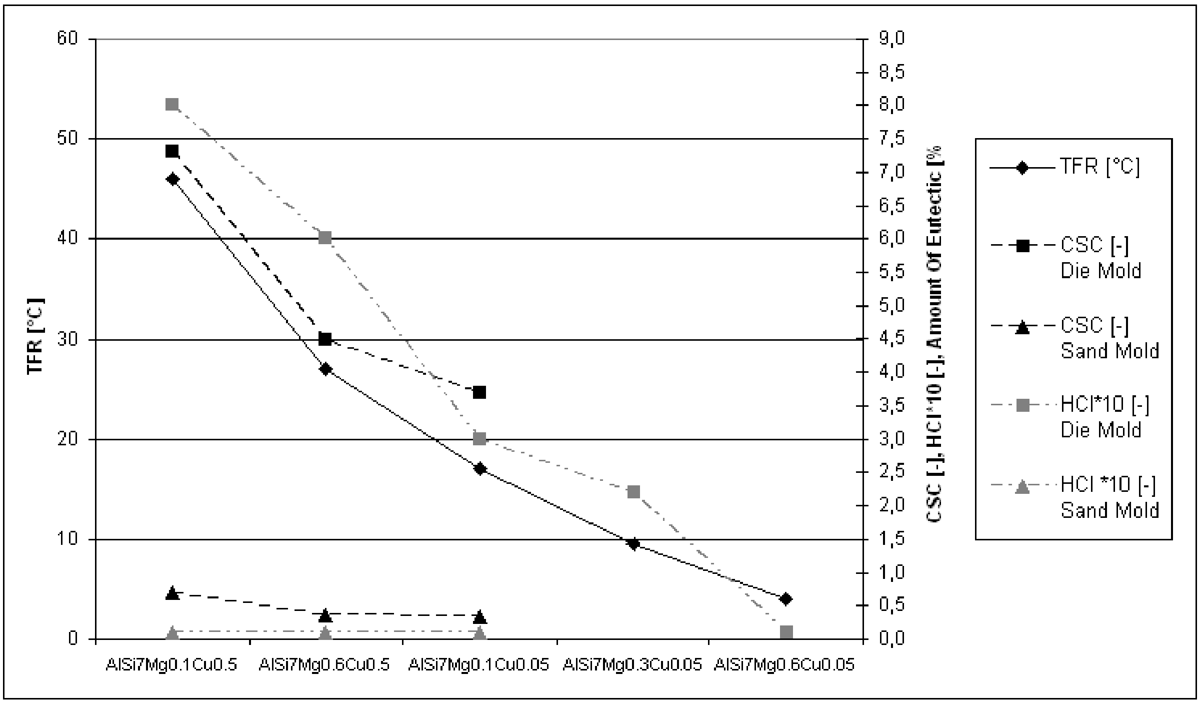

Figure 8. Trend lines of TFR, CSC and HCI for different AlSi7MgCu-alloys for theoretical and experimental methods for measuring hot cracking susceptibility.

Discussion

A brief overview of influencing factors on hot cracking was given. Five different AlSi7MgCu-alloys with varying Mg and Cu content were evaluated with three methods: theoretical TFR (Gulliver-Scheil condition), semi-empirical CSC model (Gulliver-Scheil condition) and experimental HCI examination.
In contrast to the review for DC casting by Eskin et. al [4] all three performed examinations indicate the same trend (see also Fig.8): The Cu-content has a dominating influence on hot cracking susceptibility in AlSi7MgCu-alloys. A high Cu-content results in a large hot cracking susceptibility (large TFR, high HCI and high CSC), a high Mg-content results in small hot cracking susceptibility (small TFR, low HCI and low CSC). Furthermore, theoretical predicted phases were also found in SEM investigations. At higher Cu-concentrations Cu-phases segregate in form of Al_2CuMg, $Al_5Cu_2Si_6Mg_8$ and Al_2Cu during solidification; this has a negative effect and depletes the alloy of eutectic available for micro feeding. Despite the fact that the grain size in sand casting is larger, in general a lower hot cracking susceptibility is observed in sand casting. The amount of precipitated Mg-containing phases in the eutectic in as-cast alloys is higher in sand casting than in die casting. Moreover, the soft sand mold can accommodate shrinkage strains. For AlSi7MgCu-alloys of similar grain size a good correlation between theoretical models and the experimental hot cracking index method was observed as a material property.
Especially for the development of new casting alloys a theoretical tool to forecast the hot cracking susceptibility is of major interest. Experimental evaluation of hot cracking tendency is intricate. TCC calculations are an adequate method of predicting the hot cracking susceptibility qualitatively.

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