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Evaluation of Surface Chemical Segregation of Semi-Solid Cast Aluminium Alloy A356

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Abstract. In order for SSM forming to produce homogeneous properties in a casting, it is important that there is a uniform distribution of the primary grains. Besides producing a sound casting free of porosity, the amount of liquid segregation must be minimized. The surface liquid segregation phenomenon was investigated on high pressure die cast (HPDC) A356 alloy. SSM slurries were prepared using the CSIR Rheocasting System and plates of 4mm × 80mm × 100mm were HPDC. The chemical composition depth profile from the surface was determined using optical emission spectroscopy (OES) and glow discharge optical emission spectroscopy (GDOES). It was found that a 0.5-1.0 mm eutectic rich layer existed on the surface of the alloy. The thickness of the segregation layer depended on the location on the casting. It was found that this layer was insignificant close to the gate of the casting but was relatively consistent over most of the plate. Although this segregation layer did not impact on the bulk mechanical properties, hardness tests did reveal that this region had significantly higher hardness values which may have a considerable impact on the fatigue properties.

Introduction

Semi-solid metal (SSM) forming has gained increasing interest from the automotive industry and to a lesser extent the aerospace industry because it demonstrates the capability of producing near-net shaped components with good mechanical properties. The nature of the SSM slurry - solid spherical grains suspended in liquid - makes it prone to liquid segregation during the forming process. This may manifest itself as bulk segregation or micro-segregation, depending on the alloy, die design and forming parameters.

There have been a number of reported studies investigating the modeling and quantifying typical segregation phenomena in SSM forming [1-5]. These articles mainly focused on bulk segregation to establish appropriate die design methodology. It was demonstrated that die design had a significant impact on the degree and location of liquid segregation. Regions of high strain rate were found to have a higher liquid fraction [3]. This would imply that regions of shear rate would have higher liquid content. The segregation of chemical constituents during the forming process is an important problem that needs to be understood since this will have a significant effect on the homogeneity of mechanical properties.

In recent studies on heat treatment parameters for SSM high pressure die cast (HPDC) A356 aluminium alloy components performed by the authors, a surface chemical segregation phenomenon was observed. This manifested itself by higher surface hardness values for the specified alloy composition. As a result, a focused study into this surface segregation effect was undertaken. This paper will present the general surface segregation phenomena observed for SSM HPDC A356 aluminium alloy.

Experimental Procedure

A356 alloy with a bulk chemical composition shown in Table 1 was melted using a 20kg resistant melting furnace. SSM slurries of the alloy were prepared using the CSIR-RCS [6]. Plates (Fig. 1) were HPDC using a 50t Edgewick HPDC.

Table 1: Chemical composition (wt%) of alloy A356

Si	Mg	Fe	Cu	Mn	Zn	Ti	Sr
7.14	0.36	0.10	0.01	0.01	0.01	0.07	0.02

The surface chemical composition was measured using a Thermo Quantris Optical Emission Spectrometer (OES) which had been calibrated for Al-Si alloys. The chemical composition profile was measured at the top and bottom of the plate (Fig. 1). The depth profile was determined by first measuring the chemical composition of the as cast surface. Material was then removed by a grinding process followed by measurement of the amount of material removed and chemical analysis. Chemical profiles of the main alloying elements were plotted for the cross-section of the plate. These results were validated using glow discharge optical emission spectroscopy (GDOES).

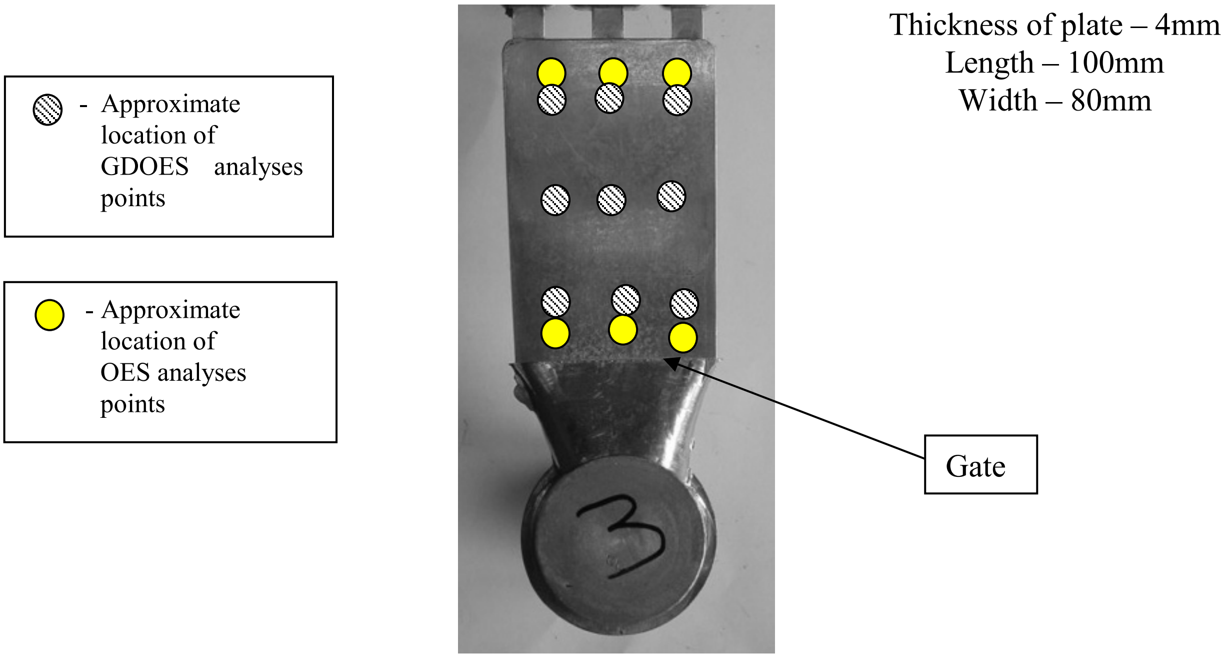


Figure 1: Image of a SSM HPDC plate showing the approximate location for the OES and GDOES analyses

Metallographic samples of cross-sections of the casting were prepared and evaluated using an optical metallurgical microscope. Vickers Hardness tests (20 kg) were performed on the as cast surface and of the bulk metal to obtain an indication of the impact on the mechanical properties.

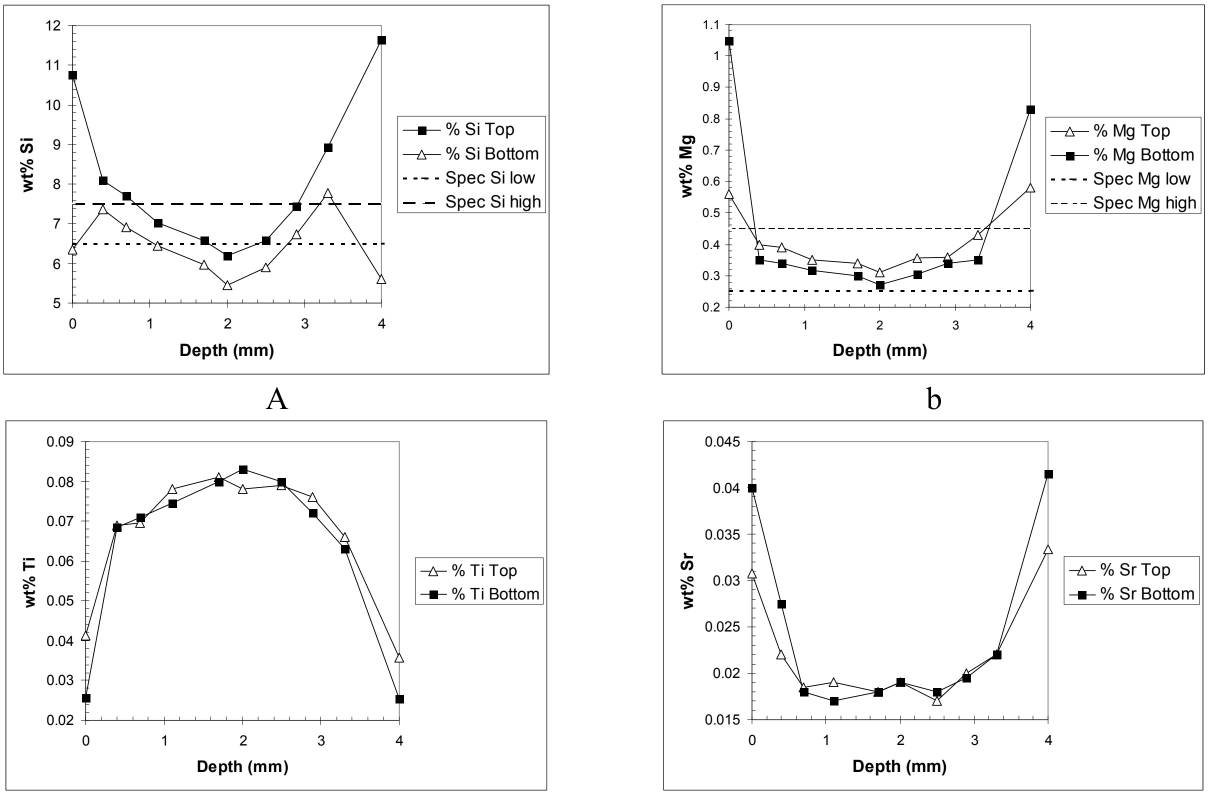
Results and Discussion

Chemical Analysis. Chemical analysis depth profiles of the main alloying elements determined using the OES are shown in Fig. 2. Two regions on the plate were investigated, close to the top of the plate and close to the gate. In the region close to the top of the plate the surface Si, Sr and Mg contents were relatively high while Ti content was relatively low. The Si content drops significantly towards the centre of the plate, dropping below the minimum specification for the alloy.

Si, Sr and Mg are typical alloying elements that would be found in the eutectic of the A356 alloy, hence indicating that the regions with high content of these alloying elements were regions of high liquid content. Using the Si high spec as the criteria, it can be seen that the liquid segregation layer can be as high 1.1 mm (measured at the top of the plate). The Ti content displayed the opposite behaviour. This had occurred since Ti was a grain refiner for the primary α phase and would hence be present where the α grains would be of highest density.

At the bottom of the plate, close to the gate, the silicon content was found to be relatively low at the surface, increasing to peak at a depth of approximately 0.4mm on one side of the plate and 0.7mm on the opposite side. The Si content distribution profile through the balance of the cross-section was very similar to that observed at the top.

Similar surface segregation effects were observed by P.K. Seo *et al* [5]. The segregation behaviour observed is as result of a combination of the gate shape and injection parameters used. The gate shape and injection parameters for this particular study were not optimized for minimizing or eliminating liquid segregation.



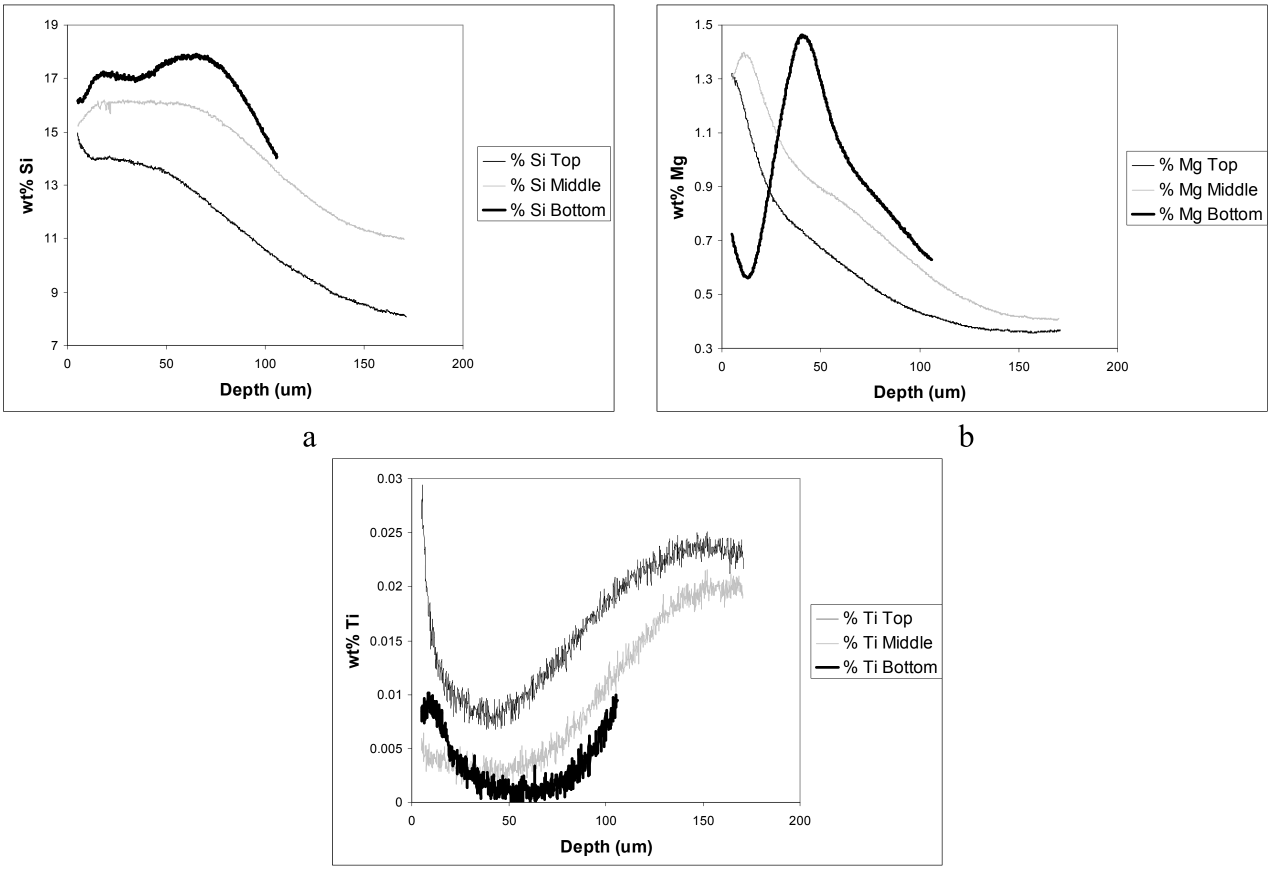
A b

C d

Figure 2: OES chemical analyses depth profiles for a) Si, b) Mg, c) Ti and d) Sr

In order to confirm the presence of surface segregation layer, surface compositional depth profiles were investigated using a GDOES. It should be noted that these results are qualitative and can only be used for evaluation of compositional trends. The maximum depth that the apparatus could produce reliable results was approximately 0.2mm. Since the spot size was approximately half that of the OES (5mm compared to 10mm), the analysis was more sensitive to localized segregation. Due to technical limitation of the analytical equipment, the chemical analysis at the bottom of the plate was done at a location slightly higher (further away from the gate) than that of the tests performed using the OES. This revealed a significant difference in the Si content profile (Fig. 3a), showing a higher Si content than the bottom and top regions. Although these results where not exactly the same as that observed on the OES, the depth profile of the main alloying elements (Fig. 3) were very similar, confirming the existence of a segregation layer.

It is evident from these results that the segregation effect is a general phenomenon that occurs on the surface of the component. The region close to gate shows a slightly different behaviour with a liquid segregation band 0.4-0.7mm below the surface (Fig. 2a). This had occurred because of a poor gate design resulting in poor filling characteristics around the gate region.



a

b

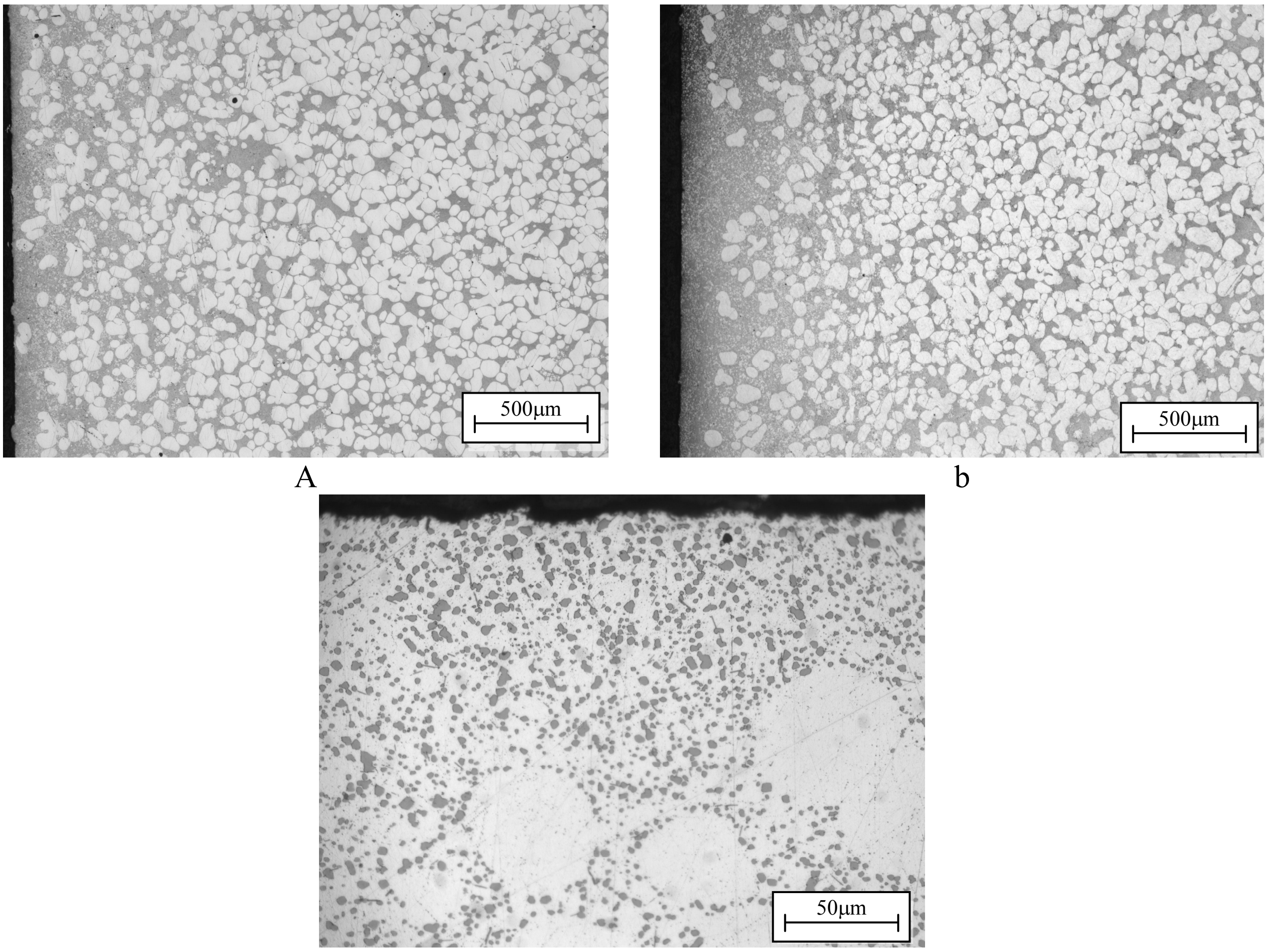
C

Figure 3: GDOES Chemical analysis profiles for a) Si, b) Mg and c) Ti

Microstructures. Microstructural analyses of cross-sections close to top and bottom of the castings (in the as cast condition) (Fig. 4a&b) revealed the presence of the liquid segregation band. The region close to the surface was composed of mainly eutectic while closer to the centre of the casting microconstituents were mainly globular α primary grains and smaller amounts of eutectic. The microstructure at the centre of the casting was more homogenous.

It was evident from the solution heat treatments that homogenization of the surface segregation effects was not possible. Microstructural analysis of the region close to the surface after a T4 heat treatment showed (Fig. 4c) that there was a structural change in the eutectic structure only, namely spheroidization of the Si.

Hardness Tests. Vickers hardness tests of the as cast surface and core of the casting (Table 2) showed a significant difference. The hardness at the surface correlated very closely to the hardness of the eutectic zone (Fig. 5). This indicates that the mechanical properties of the surface of the casting will be significantly different to the core of the casting; hence, hardness values performed on the surface of a casting does not give a true indication of bulk hardness properties.



A

b

c

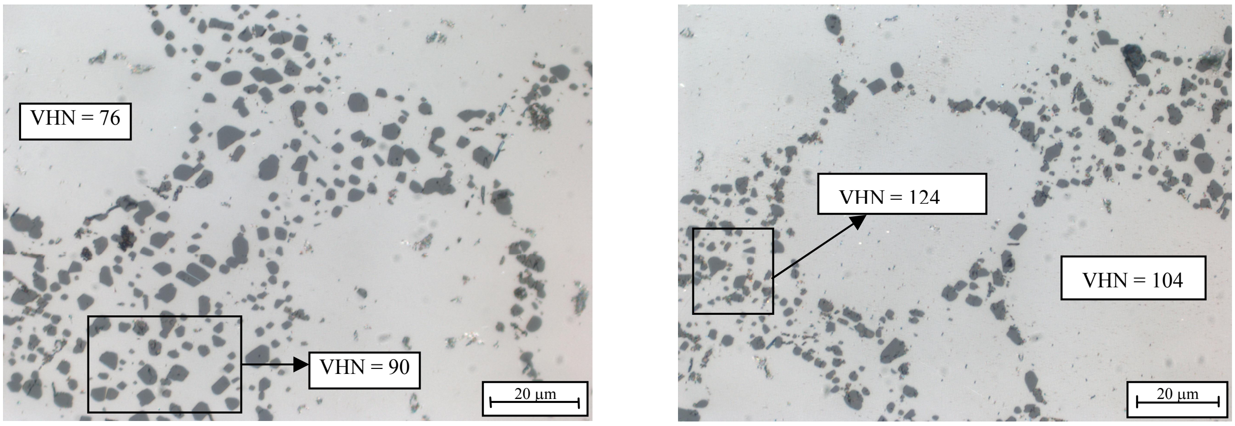
Figure 4: Micrographs of cross-sections a) close to the top, b) close to the bottom and c) after T4 heat treatment (540ºC for 6 hours followed by natural aging for 120 hours)

Although the surface hardness was higher than the material in the centre of the casting, this did not have an impact on the bulk tensile properties of the casting. This behaviour had occurred because the segregation layer at the surface was relatively small compared to the cross-sectional area. It is, however, believed that this phenomenon will have an impact on the fatigue behaviour of the alloy.

Table 2: Hardness of the plates without removing the segregation layer and after the surface segregation was removed.

Temper	**Surface VHN**	**Centre VHN**	**% Difference between Centre and Surface**
F	80.2	77.0	4
T4	89.3	80.4	10
T6	122.3	105.4	14

General. The current study was performed on a die which was not optimized. It is evident from literature [1,4,5] that die design, especially the gating design will have a significant impact on segregation effects during casting. The casting parameters used was that developed to produce porosity free castings for the die used. These parameters will also have to be researched further to establish the impact of casting parameters on surface segregation.



A b

Figure 5: Micro-Vickers hardness values of the eutectic and α grains after a) T4 and b) T6 HT

Although the die design was not optimized, it is believed that the surface segregation phenomenon observed is a characteristic of SSM forming. In order to establish this, preliminary surface chemical analyses of components cast previously on a 400t Buhler HPDC machine, indicated a similar liquid segregation phenomenon at the surface of the castings. In a study on solutions to avoid liquid segregation in thixocasting by Kang and Jung [3], it was concluded that liquid segregation was higher in the regions of higher strain rate. The liquid segregation observed at the surface of the casting in principle should be expected since the highest shear rates are experienced on the surface of the mold.

It is postulated that liquid segregation at the surface of the SSM HPDC castings is phenomenon of SSM forming. The degree of segregation will be dependent on alloy composition, die design and processing parameters. Although it does not have a significant impact on the bulk tensile properties, the effect on fatigue properties needs to be investigated further. Also the impact on corrosion and coatings will have to be evaluated.

Conclusions

Based on experimental studies of SSM HPDC plates it was established that a surface liquid segregation (SLS) phenomenon existed. The SLS layer varied between 0.7 and 1.1mm from one face to the opposite face of the casting. The hardness of this was approximately 4% higher for the as cast condition, 10 % higher after T4 HT and 14% higher after T6 HT. It is postulated that this SLS phenomenon will occur even with an optimized die and will need to be studied further to obtain a better understanding of the influence of processing parameters and alloy composition.

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Semi-Solid Processing of Alloys and Composites X
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