

## R-HPDC in South Africa

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**Abstract.** The history of semi-solid metal forming and in particular rheo-high pressure die casting at the Council for Scientific and Industrial Research in South Africa is discussed. Processing flexibility is demonstrated on the Al-Si-Mg, Al-Mg-Si, Al-Cu-Mg and Al-Zn-Mg-Cu casting and wrought alloy systems as well as on high purity aluminium, unmodified Al-Si binary eutectic, metal matrix composites and magnesium alloys. Material properties are highlighted.

### Introduction

The Council for Scientific and Industrial Research (CSIR) in South Africa has a long history of semi-solid processing and the aim of this paper is to highlight developments and achievements of the CSIR R-HPDC Technology.

### CSIR SSM history

The CSIR has been actively involved in research and development (R&D) in the field of semi-solid metal (SSM) forming for the past 12 years. In the period 2000 to 2003 a project was launched at the CSIR in the area of SSM forming which was funded by the Innovation Fund. During this period the CSIR, with its research partners, developed a process to prepare liquid metal to the semi-solid state [1] for forming via high pressure die casting (HPDC) or other techniques which was provisionally patented in 2004 and finally filed in 2008 [2]. This project was predominantly funded by the CSIR from 2003 to 2005. The project was further funded by the CSIR together with the Department of Science and Technology (DST) through the Light Metals Development Network (LMDN) under the Advanced Metals Initiative (AMI) from 2006 to date.

### CSIR Rheocasting System

The CSIR focused on commercialising this process together with fundamental research on SSM forming since 2003. The development of a commercial prototype of the patented process, now referred to as the CSIR Rheocasting System (CSIR-RCS) Device was manufactured and commissioned in 2004. In 2005 and 2006 demonstration of the process in an industrial environment was attempted by using a local industry partner. An industrial scale HPDC research facility was established at the CSIR in 2008-2009 using infrastructure funding sourced from the LMDN project, due to the difficulty in accessing commercial HPDC facilities for assessing the technology. Research and development at the CSIR has made significant progress since establishing this laboratory. The research team has focussed on optimising the CSIR-RCS for process stability and energy consumption. Opportunities and challenges of applications of this system for the aerospace and automotive market have been discussed [3-5].

### R-HPDC Cell

The technology of pairing the CSIR-RCS device with a high pressure die casting (HPDC) machine is termed rheo-high pressure die casting (R-HPDC) and in South Africa is called the CSIR R-HPDC Technology. Currently there are two versions of the CSIR R-HPDC Technology distinguished by its scale of operation. Figure 1 shows the two different cell scales with all the cell elements while Table 1 gives a basic overview of the specifications for the cell elements.

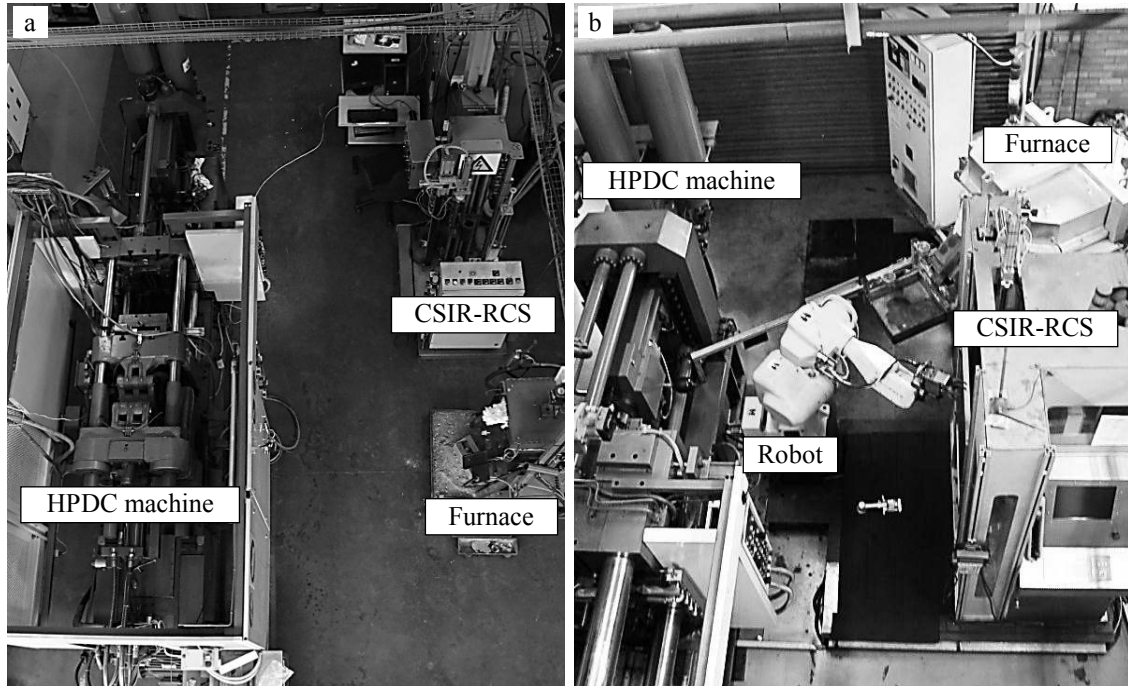


Figure 1. CSIR R-HPDC Cell arrangements (a) small scale and (b) large scale.

Table 1. Basic specifications for cell elements of the small and large scale CSIR R-HPDC Cells.

Cell element / Function		Small scale cell	Large scale cell
CSIR RCS Device	Model	<i>Ice</i>	<i>ICe</i>
Furnace	Make	Custom	Westofen
	Type	Ladle	Controlled dosing
	Capacity	25 kg	240 kg
HPDC machine	Make	LK	LK
	Model	DCC130	DCC630
	Type	Shot control	Shot control
Material transfer	Type	Operator	Robotic
	Make	-	Fanuc
Element integration	Type	None	Computer control
Operation	Type	Manual	Automatic / Manual

The main difference, besides scale, is the mode of material transfer between the cell elements. The small cell is manual operator based while the large cell is automatic robot based. The basic sequence of operations in the cell is the following. Liquid alloy metal is ladled or dosed from the furnace into the processing cup. The processing cup is transferred by the operator or robot to the rheocasting system for processing. The processing cup is ejected from the rheocasting system and

transferred, again, by the operator or robot to the HPDC machine. The injection piston is triggered to follow the programmed shot profile once the semi-solid metal billet is emptied into the shot sleeve of the HPDC machine.

### Alloy processing

The CSIR-RCS demonstrates its flexibility by the ability to process a number of different types of material including aluminium casting alloys [6,7], aluminium wrought alloys [8,9], high purity aluminium [10], unmodified aluminium-silicon binary eutectic [11], metal matrix composites [12] and magnesium casting alloys [13,14].

The typical procedure to prepare for processing an alloy is by choosing the alloy composition and custom preparing the alloy if the commercial alloy is not available. The melt is prepared in the furnace and a sample is poured for chemical analysis with an optical emission spectrometer (OES) on site. Melt parameters have also been investigated [15]. The actual composition from the OES is then used as input to a thermodynamic database to calculate the theoretical thermal properties of the liquid alloy including the liquidus temperature and the 0.3 solid fraction temperature ( $f_s^{0.3}$ ). The pouring temperature with a superheat of between 10 and 20 °C is calculated and the furnace temperature is set to stabilise and control at the calculated pouring temperature. Processing is ready to commence at this point.

The processing sequence starts by ladling the liquid alloy into the processing cup and transferring to the CSIR-RCS. The cup is positioned in the processing coils where the cooling rate is controlled by the forced air cooling while the stirring action is controlled by the power input into the induction coil [2]. Processing continues until the  $f_s^{0.3}$  temperature is reached at which point the processing cup is ejected from the processing coil. The SSM material in the cup is then transferred to the HPDC machine and emptied into the shot sleeve and subsequently HPDC.

Resultant as-cast microstructures of alloy systems cast using the CSIR R-HPDC Technology is presented in Figure 2 through Figure 9. Each figure will be discussed in short. Microstructures of alloy systems only are shown in this section because of the similarity in structure within a system regardless of the specific alloy.

**Al-Si-Mg alloys.** Figure 2 is typical light optical microscope (LOM) image of a hypoeutectic Al-Si-Mg alloy (A356 and F357). The primary-(Al) grains (light grey) are globular with a high spherical shape factor. Grains with a lower spherical shape factor and larger aspect ratio are also visible and their shape mainly depends on their actual position in the magnetic field during stirring. The other feature of this type of alloy is the fraction of eutectic visible (dark grey). The structure of the Si in the eutectic is very fine indicating modification. Modification could either be the result of chemical addition to the alloy like Sr or Na for instance. But modification is also a result of a high cooling rate as the case with HPDC.

**Al-Mg-Si alloys.** Figure 3 is a LOM image of the microstructure of an Al-Mg-Si alloy i.e. AA6082. This microstructure is characterised by a very large fraction of primary-(Al) grains. The grains are globular and relatively large and more rosettes are also visible indicating a small number of nuclei at the start of solidification and a long period of grain growth during rheo-processing. Fe based intermetallics as well as Mg<sub>2</sub>Si are found in the inter-globular regions. Mg and Si is the base for precipitate strengthening during heat treatment while the Fe intermetallics are detrimental to ductility of the alloy.

**Al-Cu-Mg alloys.** Figure 4 shows a scanning electron microscope (SEM) back scattered image (BSI) of an Al-Cu-Mg alloy i.e. 2139. Again the microstructure is primarily equi-axed primary-(Al) globular grain and the light phase is the eutectic of Cu and Mg alloying elements and minor alloying elements if added.

**Al-Zn-Mg-Cu alloys.** Figure 5 this time shows a SEM BSI of an Al-Zn-Mg-Cu alloy i.e. 7076. The microstructure is dominated by equi-axed primary-(Al) globular grains and the light phase in this case is the eutectic of Zn, Mg and Cu alloying elements also with minor alloying elements if added. It is indeed difficult to distinguish between the microstructures of Figure 4 and 5.

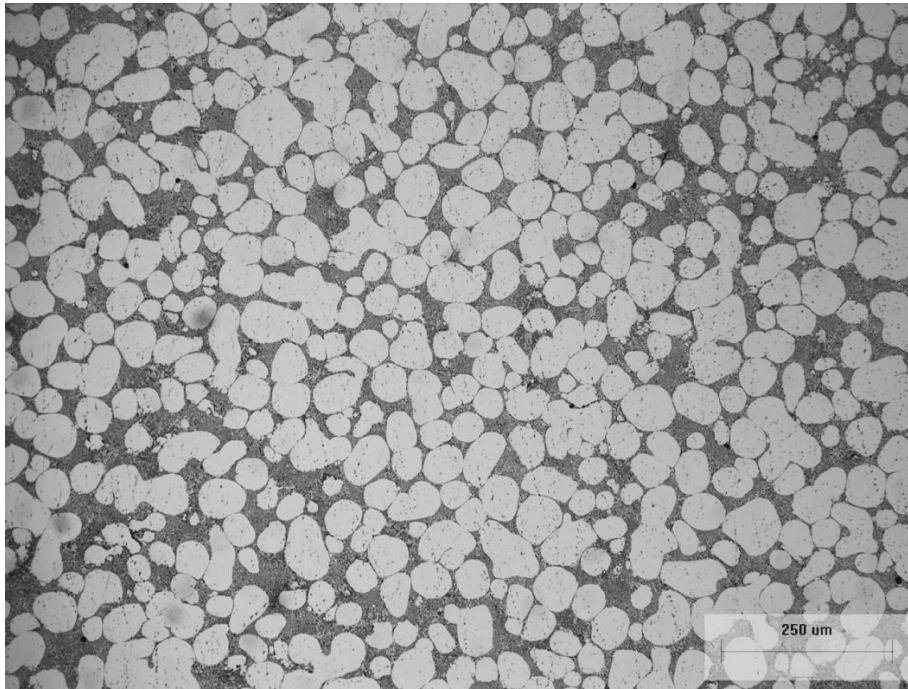


Figure 2. As-cast microstructure of a CSIR R-HPDC Al-Si-Mg alloy.

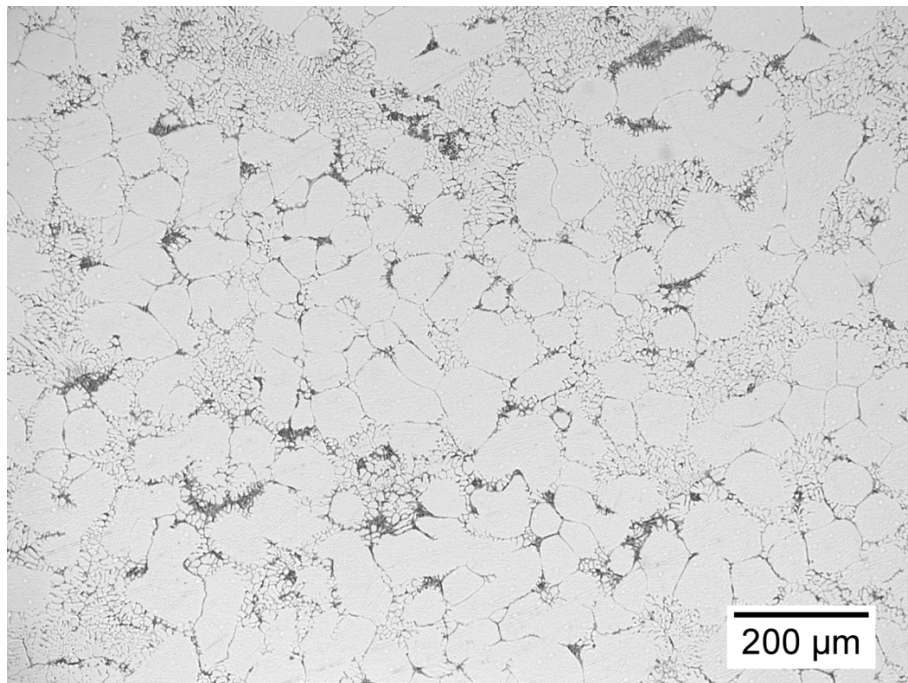


Figure 3. As-cast microstructure of a CSIR R-HPDC Al-Mg-Si alloy. [8]

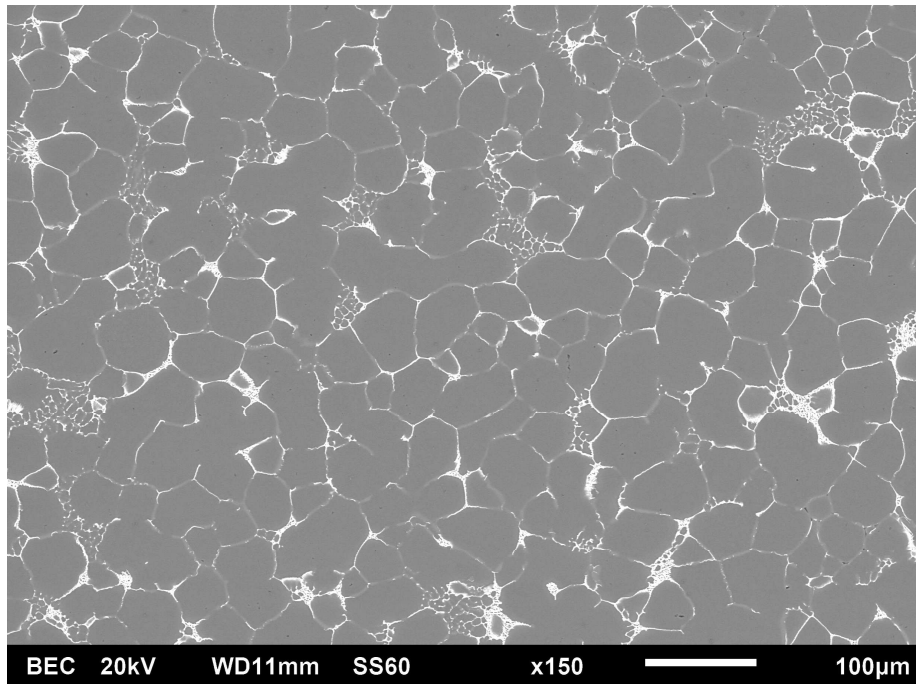


Figure 4. As-cast microstructure of a CSIR R-HPDC Al-Cu-Mg alloy.

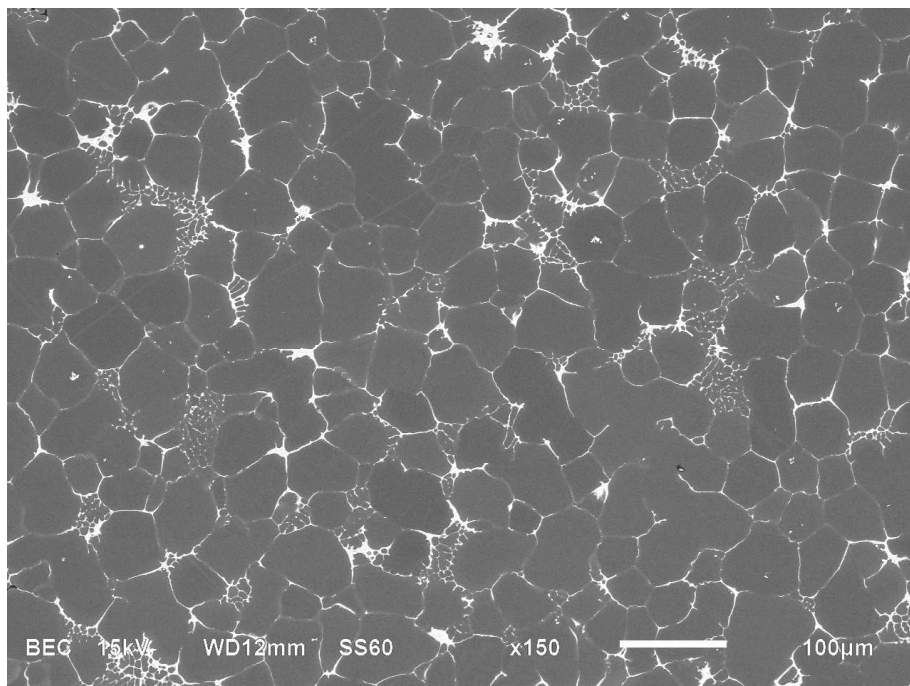


Figure 5. As-cast microstructure of a CSIR R-HPDC Al-Zn-Mg-Cu alloy.

**High purity aluminium.** Figure 6 shows the microstructure of CSIR R-HPDC high purity Al which is unique. Solidification of pure metals is an invariant reaction which does not exhibit a solidification temperature interval like alloys. It is possible to semi-solid cast pure metals on account of the solidification time interval which is related to the latent heat of fusion of the metal and the cooling conditions [10]. The grain structure is evaluated in detail during this conference [16].

**Unmodified Al-Si binary eutectic.** Figure 7 shows a LOM image of an unmodified Al-Si binary eutectic. The invariant reaction argument and the principle of a solidification time range is the same in this case as for high purity Al above. The structure is unintuitive on account that the two phase grains are not modified as in the case of a slow cooling rate while the inter-grain regions has a

modified structure characteristic of a high cooling rate. Note that it does not make sense to refer to either the coarse or fine structure as the eutectic because the whole alloy has the binary eutectic composition. [11]

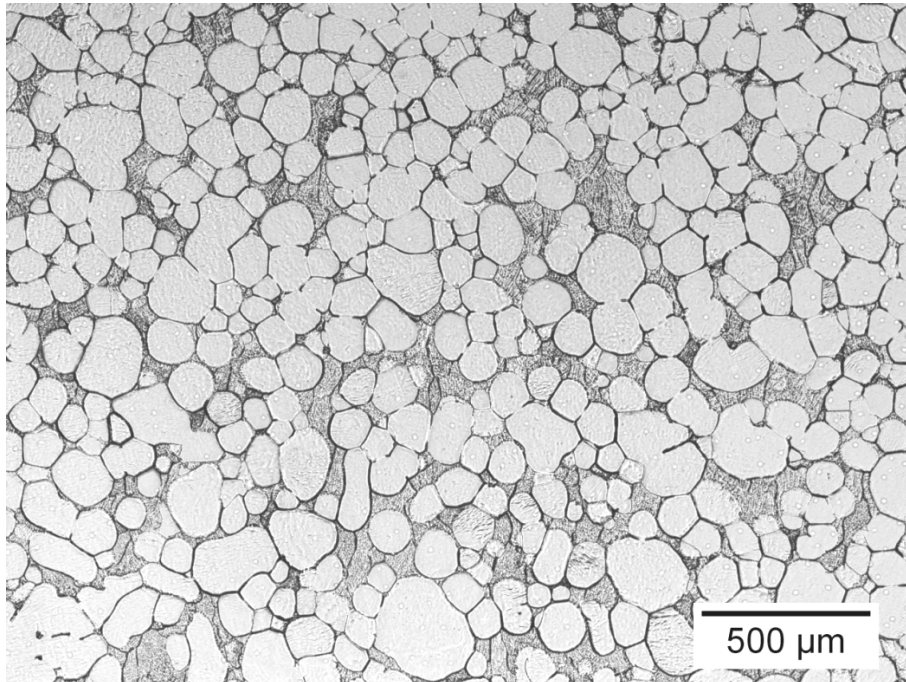


Figure 6. As-cast microstructure of a CSIR R-HPDC high purity Al. [10]

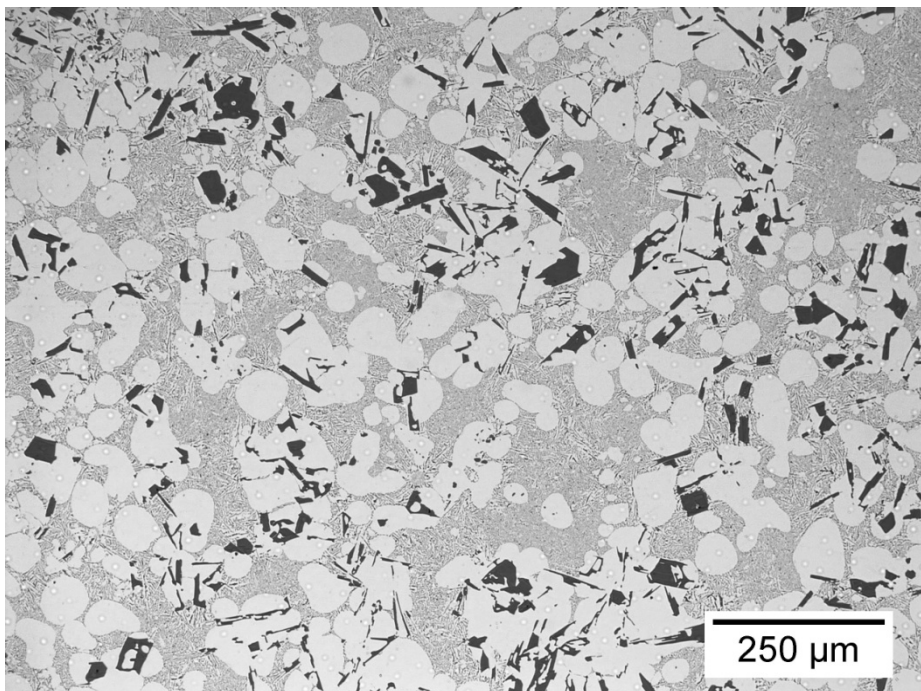


Figure 7. As-cast microstructure of a CSIR R-HPDC unmodified Al-Si binary eutectic. [11]

**Metal matrix composites.** Figure 8 shows a LOM image of a CSIR R-HPDC SiCp/A359 metal matrix composite (MMC). A359 is a hypoeutectic Al-Si alloy and has the same features as Figure 2 except that there are SiC particles dispersed throughout the eutectic in the inter-globular regions while the primary-(Al) grains are still equi-axed.

**Mg-Al alloys.** Figure 9 shows a LOM image of a hypoeutectic Mg-Al alloy and again as in all the cases above is characterised by a globular primary-(Mg) with an inter-globular eutectic phase indicative of non-equilibrium solidification and is presented at this conference [14].

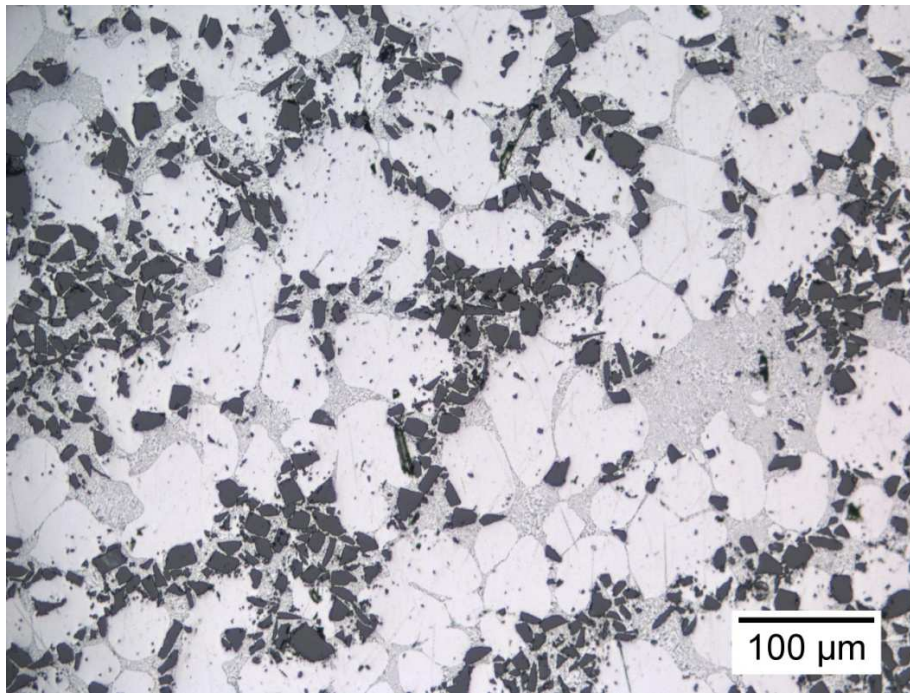


Figure 8. As-cast microstructure of a CSIR R-HPDC SiCp/A359 MMC. [12]

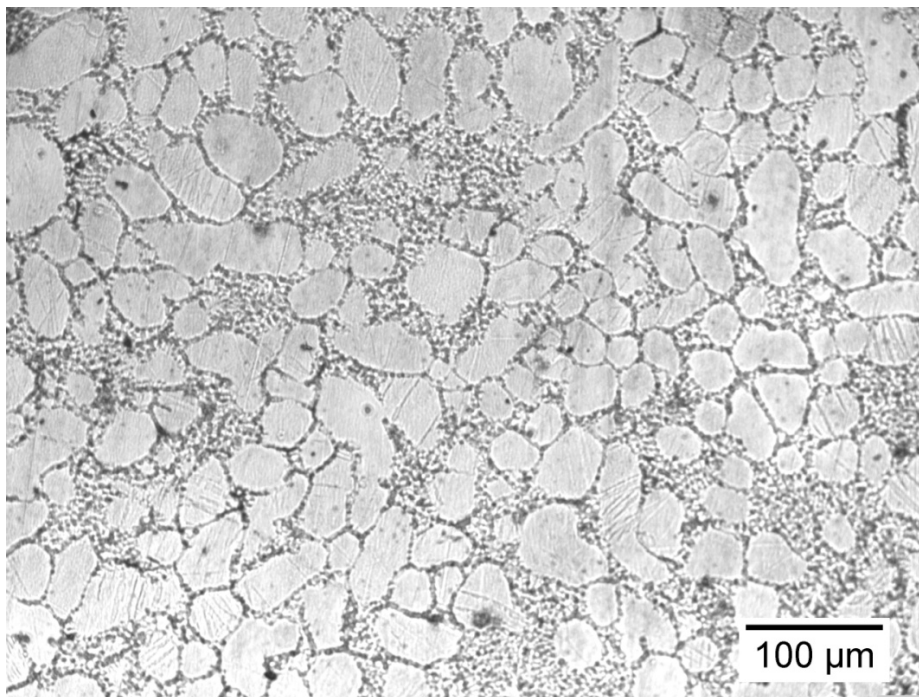


Figure 9. As-cast microstructure of a CSIR R-HPDC Mg-Al alloy.

**Surface Liquid Segregation.** Surface liquid segregation is characteristic of all SSM processes, especially rheocasting processes, in all components and has been characterised in Al-Si-Mg [17], Al-Cu-Mg and Al-Zn-Mg-Cu [18] alloys.

### Component production

The CSIR has four die sets to produce components on the different R-HPDC Cell scales. Figure 10 shows that plate and taper rod components used on the small scale for basic research i.e. microstructure characterisation, homogenisation and solution heat treatments, optimisation of artificial ageing heat treatments, measuring tensile properties, corrosion and welding.

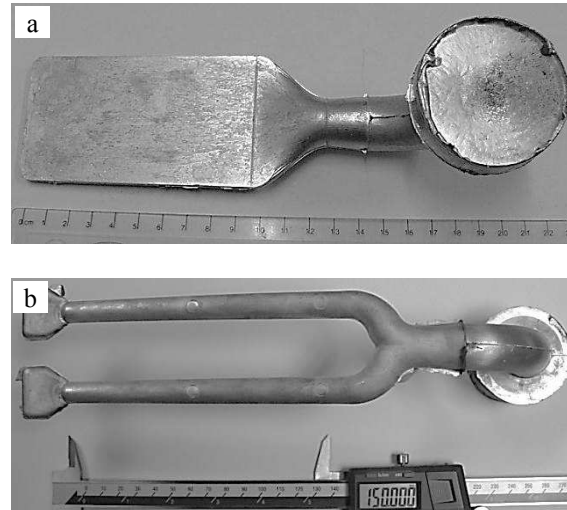


Figure 10. Small scale research components (a) Plate [10] and (b) Taper rods.

Figure 11 shows the two industrial components, an automotive brake calliper and an engine mounting bracket, for the large scale R-HPDC Cell to characterise and evaluate the CSIR R-HPDC Technology on an industrial scale. The brake calliper in an Al-Si-Mg alloy [19] and the engine mounting bracket in an Al-Zn-Mg-Cu alloy [20] were evaluated. Laboratory scale heat treatment for tensile property evaluation was reported before [21] while the industrial scale heat treatment is reported in this conference [22].

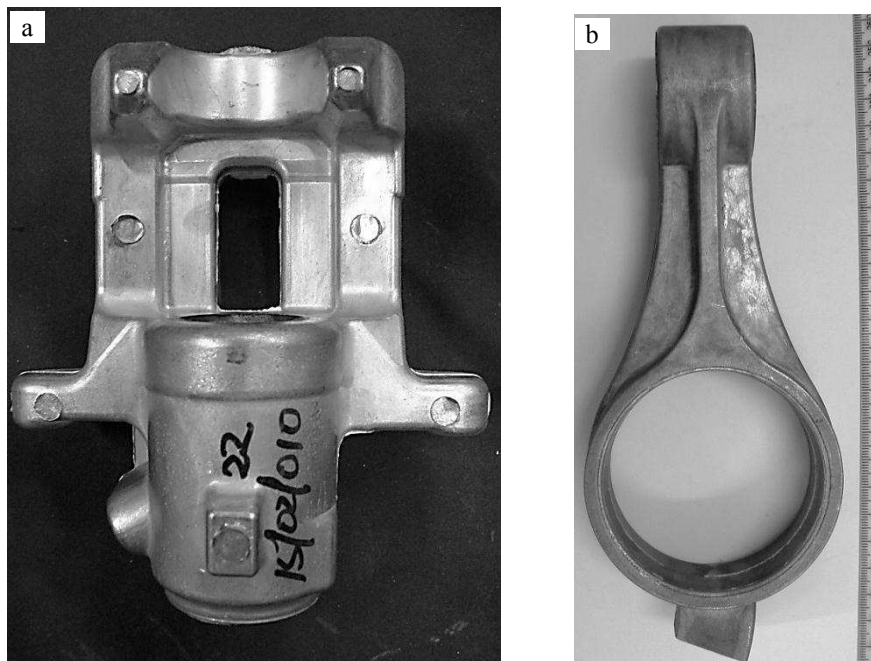


Figure 10. Large scale industrial research components (a) Brake calliper [19] and (b) Engine mounting bracket [20].



## Material properties

**Tensile properties.** The first aim of heat treating SSM processed heat treatable alloys is to achieve, at least, the minimum tensile properties specification. The next step is to work towards the typical properties of the specific alloy in the same heat treated condition. Table 2 is a collation of some of the tensile properties achieved for specific alloy system designations; indicated here for self comparison.

Table 2. Collated table of CSIR R-HPDC T6 and some T4 tensile properties for heat treatable aluminium alloys by alloy system. A number of magnesium alloys are included.

<i>Alloy system</i>	<b>YS [MPa]</b>	<b>UTS [MPa]</b>	<b>Elongation [%]</b>	<b>Reference</b>
<i>Al-Si-Mg</i>				
F357 <sup>#</sup>	176	299	18.0	[34]
F357	304	365	10.6	[34]
<i>Al-Mg-Si</i>				
6004	207	237	12.0	[32]
6082 <sup>*</sup>	323	344	4.2	[32]
6082 <sup>*</sup>	351	385	5.1	[8]
<i>Al-Cu-Mg</i>				
206	330	379	8.0	[7]
2024 <sup>*</sup>	351	385	5.1	[8]
<i>Al-Cu-Mg-Ag</i>				
2139	361	439	10.7	[37]
2139	423	475	6.5	[37]
<i>Al-Zn-Mg</i>				
7017	361	409	7.1	[38]
<i>Al-Zn-Mg-Cu</i>				
7076	466	515	9.0	unp.
7075 <sup>*</sup>	467	513	3.5	[8]
7150	516	537	2.0	unp.
<i>Mg-Al-Mn</i>				
AM50A <sup>*#</sup>	88	231	16.7	[14]
AM60B <sup>*#</sup>	89	226	12.1	[14]
<i>Mg-Al-Zn</i>				
AZ91D <sup>*#</sup>	104	267	12.3	[14]

\*: Commercial

#: T4

unp.: Unpublished

The largest part of fundamental research at the CSIR was focused on the Al-Si-Mg alloy system, investigating topics including various heat treatment conditions [23-26], heat treatment time and temperature response [27,28], the effect of elevated impurity levels [29], comparing dendritic and globular microstructures [30]. The Al-Si-Mg casting alloy system was compared to the Al-Mg-Si wrought alloy system for which the strengthening mechanism is similar [31,32]. The factors

influencing tensile properties for the Al-Si-Mg system was also delineated [33]. Ultimately, atom probe tomography (APT) was used to uncover the mechanism for precipitation strengthening in this system [34].

The effects of minor alloying elements were investigated [7,35] as well as a solution heat treatment optimisation for the Al-Cu-Mg alloy system [36]. Heat treatment of a Al-Cu-Mg-Ag alloy is the topic of presentation in this conference [37].

Heat treatment of an Al-Zn-Mg alloy is presented at this conference [38] while solution heat treatment of an Al-Zn-Mg-Cu alloy was studied before [39].

**Corrosion.** It is expected that the effect of the surface liquid segregation layer will have an impact on corrosion properties of castings. Pitting was investigated for an Al-Si-Mg alloy [40] while corrosion was investigated for Cu-containing wrought alloy systems [41].

A corrosion comparison of HPDC and R-HPDC magnesium alloys is presented at this conference [42].

**Welding.** Laser welding of Al-Si-Mg was investigated on a number of occasions [43-45] as well as the effect of a number of heat treatments on the welds [46-48]. Property and quality optimization of a laser welded Al-Si-Mg alloy will be presented at this conference [49].

Fusion welding of an Al-Zn-Mg alloy will also be presented at this conference [50].

## Approach

The intent of R&D at the CSIR is to provide customers with a total turn-key solution including alloy selection, alloy processing, die design, HPDC optimisation and heat treatment optimisation to produce components with final requisite material properties. These properties are not limited to tensile properties but include fatigue, impact, stress corrosion cracking, anodising, welding and wear. The aim is at reducing the risk of failure due to past mistakes by not considering the entire end to end value chain.

## Future

One of the aims is to produce a material properties database for design purposes including tensile, fatigue, impact, corrosion, welding, anodising and stress corrosion cracking properties, especially for the high strength heat treatable aluminium alloy systems. There is a market for SSM technology and the designed components must be chosen such that they make both technical and economic sense and the aim is to create awareness for the fit-for-purpose design.

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