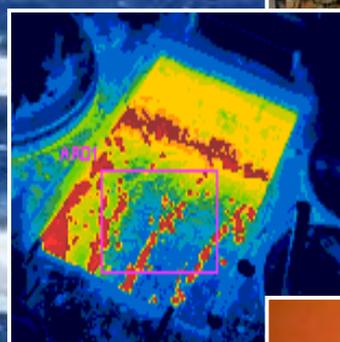


# Manufacturing of Magnesium Components

**Final Report VAMP 32**

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## Preface

This report is a result from research project conducted 2003-2005 concerning die casting and surface treatment of magnesium and how the processes affect the corrosion resistance and mechanical properties.

The project was sponsored by the Swedish Agency for Innovations System (Vinnova) via the research program VAMP (Verkstadsindustrins användning av material i sina produkter).

Markus Blomdahl, Swedish Foundry Association, Dan Jacobsson, KIMAB and Martin Jönsson, KIMAB have written the report based on documentation from the finished activities.

## Abstract

Magnesium alloys have low density, high specific strength, a high ability to shield electromagnetic radiation and good absorption of sound and vibration. These properties have created a great deal of interest for the use of the alloys in the motor industry, in the aerospace industry, and for hand-held products. All of these industries deal with applications in which weight is extremely important.

This project has been sponsored by the Swedish Agency for Innovations System (Vinnova) and by a number of Swedish manufacturing companies. The aim of the project has been to increase the knowledge of manufacturing of magnesium concerning high pressure die casting and surface treatment and corrosion properties. The project was led by the Swedish Foundry Association and KIMAB.

The project has shown that the product quality can be improved, and that the production cost and environmental load can be decreased. This can be achieved by fairly small efforts. Activities concerning die casting has shown that a new cover gas system called AM-cover can replace a SF<sub>6</sub>-system and that the melting of magnesium can be done more efficient using the new technology AM-converter. A high degree of in-house re-circulation is feasible without negative effect on the product quality. Corrosion protection tests shows that alternative pretreatment (e.g. Alodine 160 and Oxilan Al 500) shows similar good performance compared to chrome based treatment.

## 1 INTRODUCTION

Lightweight components make it possible to lower the fuel consumption for vehicles and can also improve the ergonomics for hand-held products like machine saws and electronic devices. The total weight of an European car model has in average gained about 30 % the last 15 years [1], because of demands on better safety and comfort. Magnesium has a lot of interesting properties like a high strength / weight relationship, good absorption of sound and vibration and a high ability to shield electromagnetic radiation, which makes the material interesting to use in different applications. One example is the new composite crankcase from BMW, where the total weight has been reduced with 25% thanks to the implementation of magnesium. The use of magnesium is relatively low compared to aluminium, but the material are showing a positive trend and experts are talking about an annually growth of 10-20 % [2]. The car industry is the leading segment for this growth. European cars consist in average of 4 kg magnesium [1]. Some car models use up to 14-26 kg. It is the general opinion that this value will rise to about 60-120 kg in about five years from now, which means that the future need of magnesium components will be in average 40 times bigger than today [2].

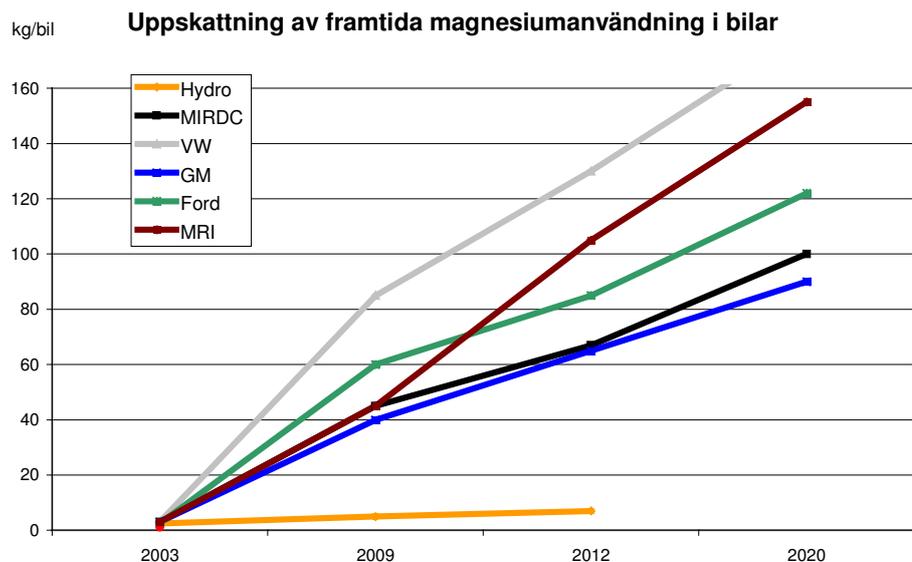


Figure 1: Estimated trends about the future use of magnesium in cars (kg / year)[1].

To be able to make this material revolution there are many obstacles to overcome. The most important is the lack of competence to construct components in magnesium. The driving forces to increase the use are often producers of magnesium and car manufactures. It is not unusual that first tier's holds back the development because of better knowledge in design and manufacturing of aluminium, steel and polymers. The total cost for the new magnesium component must also be at least equal to that for existing components or even cheaper.

In September year 2003 started a new magnesium project sponsored by the Swedish Agency for Innovation Systems (Vinnova), which was led by the

Swedish Foundry Association together with KIMAB. The project was called “VAMP 32 - Manufacturing of Magnesium Components for the Industry” and ended in December 2005. This report summarises the results from different studies that were conducted in the project.

The aim with the project was to verify if demanded technical specifications could be achieved through process optimisation and implementation of new know-how about design, manufacturing, surface treatment and corrosion protection of advanced high pressure casted magnesium components.

Target groups for the project are die casting and surface treatment companies and their customers. Both designers and production technicians could use the information in the report in order to be able to achieve a more cost and environmental efficient manufacturing of magnesium components, which also fulfils future demands on corrosion resistant, surface finish and mechanical properties.

The research was carried out in a close collaboration with the participating companies and the work was based on two subprojects called casting process respectively surface treatment and corrosion. Totally 17 companies participated in the project, for a detailed information see list below.

<b>Research Institutes</b>	<b>Contact person</b>	<b>Homepage</b>
Swedish Foundry Association	Markus Blomdahl	<a href="http://www.gjuteriforeningen.se">www.gjuteriforeningen.se</a>
Institute of metall (KIMAB)	Dan Jacobsson	<a href="http://www.kimab.se">www.kimab.se</a>
Corrosion institute (KIMAB)	Bo Rehndahl	<a href="http://www.kimab.se">www.kimab.se</a>
<b>University</b>		
School of Engineering, University of Jönköping	Magnus Wessén	<a href="http://www.hj.se">www.hj.se</a>
<b>Companies</b>		
ADC of Sweden	Jan Henriksson	<a href="http://www.adc-sweden.se">www.adc-sweden.se</a>
Advanced Magnesium Technology AMT Europe GmbH (former AMC)	Jan Bolstad	<a href="http://www.am-technologies.de">www.am-technologies.de</a>
Bodycote Ybehandling AB	Jan Sidén	<a href="http://www.bodycote.se">www.bodycote.se</a>
Chemetall AB	Mats Eriksson	<a href="http://www.chemetall.se">www.chemetall.se</a>
CSM Materialteknik AB	Karin Ölmén	<a href="http://www.csm.se">www.csm.se</a>
Finnveden Gjutal AB	Stefan Gustavsson	<a href="http://www.finnveden.com">www.finnveden.com</a>
Henkel Norden AB	Stefan Nyckel	<a href="http://www.henkel.se">www.henkel.se</a>
Husqvarna AB	Ola Ring	<a href="http://www.husqvarna.com">www.husqvarna.com</a>
Norsk Hydro ASA	Jan Ivar Skar	<a href="http://www.hydrumagnesium.com/">www.hydrumagnesium.com/</a>
Proton Finishing AB	Jan Malmqvist	<a href="http://www.proton.se">www.proton.se</a>
Scania CV AB	Petter Kylefors	<a href="http://www.scania.se">www.scania.se</a>
Tikkurila Coatings	Lennart Björk	<a href="http://www.tikkurila.se/">www.tikkurila.se/</a>
Volvo Car Corporation	Malte Isaksson/ Ingemar Bertilsson	<a href="http://www.volvocars.se">www.volvocars.se</a>

## 2 DIE CASTING

This project concerns only high pressure die casting of magnesium with cold chamber method. The method is commonly used for larger components and where a high metal pressure is needed during the contraction phase. When using the cold chamber method the melt has to be poured into the shot sleeve, using a metering pump system. The casting process is based on three phases, the piston is moving forward during the first phase until that the melt has reached the ingate of the component. The second phase is the same as the filling phase, where the cavity is filled with melt. A third phase is used to build up a high melt pressure, in order to minimise the size of trapped air bubbles inside the component. This melt pressure is one of the parameters, which determines the needed locking force and thus the machine size.

For smaller parts the hot chamber method is often used. The advantages with that method are for example higher productivity, lower melt temperatures and less oxides.

In order to reduce the thermal variation of the melt and to reduce the energy consumption, the ingots are preheated before melting to about 150 °C. Some die casters are also working with internal recycling of clean and dry scrap like as-casted components, ingates and biscuits. The recycling rate is often varied between 30-50 %.

Mainly two different melting systems are used. Both working with separated melting and holding areas. In one system the areas are constructed together in one furnace and are divided into two chambers by a wall. The other system is working with two furnaces, one for melting and one for holding the melt. To transfer the melt between the furnaces a transferring system consisted of a heated tube and metering pump are used. The crucibles are normally made of plain carbon or nickel-free low alloy steel.

The project concerns only the magnesium alloys AZ 91 and AM 50, which are based on the Mg-Al alloy system. The reason is that they are the most commonly used Mg alloys for high pressure die casting. AZ 91 is mainly used when castability, good surface finish and a high strength are required. For automotive components, where especially high ductility is needed, and the most common magnesium alloy are AM 50. The main alloying element in these alloys are aluminium, zinc and manganese. The below table shows the effects from different alloying elements are explained and how the thermal processes influence the level of them.

*Table 1: Influence of thermal process on alloy chemistry [3].*

<b>Al</b>	A slight loss of aluminium will occur during long-term holding of the melt. This is probably due to enrichment of aluminium in the oxide layer formed on the melt surface.
<b>Zn</b> <b>Si</b> <b>RE</b>	Zinc, silicon and the rare earth elements (RE = cerium +lanthanum+praseodymium+neodymium), are all highly soluble in molten magnesium alloys, and their concentration remains fairly constant throughout all melting and handling operations.
<b>Be</b>	Beryllium in amounts of 5-15 ppm is added to reduce the rate of surface oxidation of the molten alloys. It is easily lost due to preferential oxidation during holding of the melt. An even quicker loss result from thermal cycling of the melt or in cases where a metal fire takes places in the crucible.
<b>Mn</b> <b>Fe</b>	Manganese is added to magnesium alloys in order to reduce the solubility of iron to levels below the specified maximum. The contents of manganese and iron decreases quickly when the temperature is lowered followed by a slow increase as the temperature is raised again. This reflects the difference in rates of precipitation/settling versus solution of the intermetallic particles. The contents of manganese and iron are not necessarily restored to what they where originally, as iron may dissolve from the crucible wall, establishing equilibrium with higher iron and lower manganese contents.
<b>Ni</b>	Nickel is extremely detrimental to the corrosion resistance of manganese alloys and must be limited to a maximum of 0,002% in the finished parts (0,001 % in ingots). It is highly soluble in magnesium alloys and may be picked up from the processing equipment if, for instance, high nickel stainless steels are used.
<b>Cu</b>	Copper also decreases the corrosion resistance of magnesium alloys although the tolerance limit is far higher than for nickel. Contamination from copper bushings etc. in recycled parts van cause enrichment of copper to levels higher than the allowable maximum limit.

To better understand and to improve the casting process of magnesium the project team agreed on the importance of more research within the following categorises.

- Developing of the melting process system.
- Replacement of the cover gas SF<sub>6</sub>.
- Inhouse recycling of magnesium.
- How the casting process parameters affect the quality of the magnesium component.
- Analysis methods for magnesium alloys.

## 2.1 AM-converter – test of an active melting equipment

The AM-converter is a patented device that facilitates rapid melting of ingots, returns and other magnesium solids in a furnace. The device increases the melting rates, significantly reduces melt losses and cover gas consumption, and provides improved health and safety. The formation of sludge is virtually eliminated and production of dross is also significantly reduced. AM-converter are marketed by the Australian company Advanced Magnesium Technologies (AMT) [4]. AMT Pty LTD is a wholly owned subsidiary of Australian Magnesium Corporation (AMC).

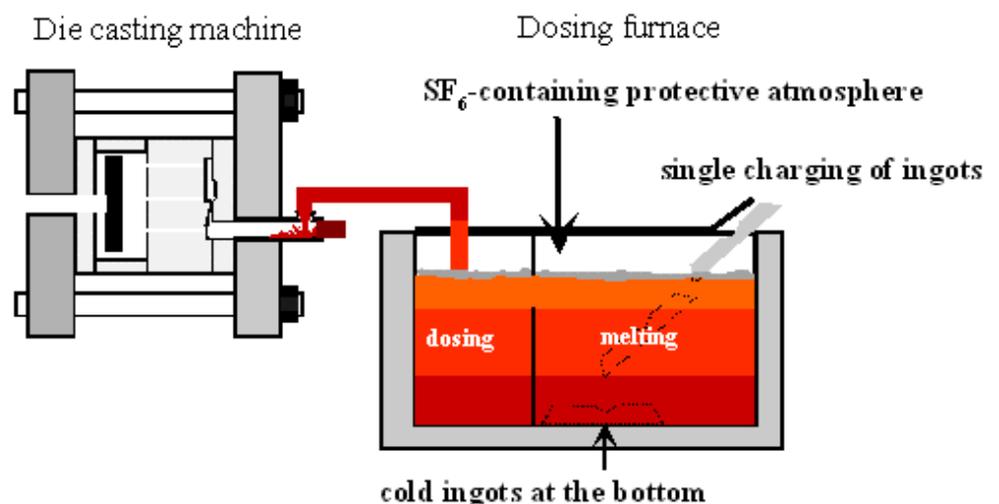
To test the new developed active melting equipment, a production test was carried out at Finnveden Gjotal AB in Hultsfred during autumn 2003. The following persons were involved during the construction, implementation and production phase of the AM-converter: Thomas Blomqvist, Swedish Foundry Association (now working for Finnveden Gjotal AB), Jan Bolstad, AMT Europe, Per Bakkedal, Nordisk Industrioven, Stefan Gustavsson, Finnveden Gjotal AB, Morgan Karlsson, Finnveden Gjotal AB and Markus Blomdahl, Swedish Foundry Association.

Before the production test at Finnveden Gjotal AB, the equipment had just been fully tested occasionally at a few die casting plants in Europe. The AM-converter used in the test was a prototype on which design was modified to meet Finnveden Gjotal equipment requirements..

### 2.1.1 Method

#### 2.1.1.1 *The melt system at Finnveden Gjotal AB*

Finnveden Gjotal AB had installed a new larger melting and holding furnace before testing the AM-converter. *Figure 2* shows a schematic picture of the furnace used. The furnace is feeding melted magnesium to a large cold chamber machine with a locking force of 2 750 tonne. Mainly large and complex components are casted in the die casting machine.



*Figure 2: Schematic picture of the melt system at Finnveden Gjotal.*

The furnace was delivered from Nordisk Industrioven and had a size of 2 700 kg and a power rating of 250 kW.

The AM-converter was installed in the melting zone.

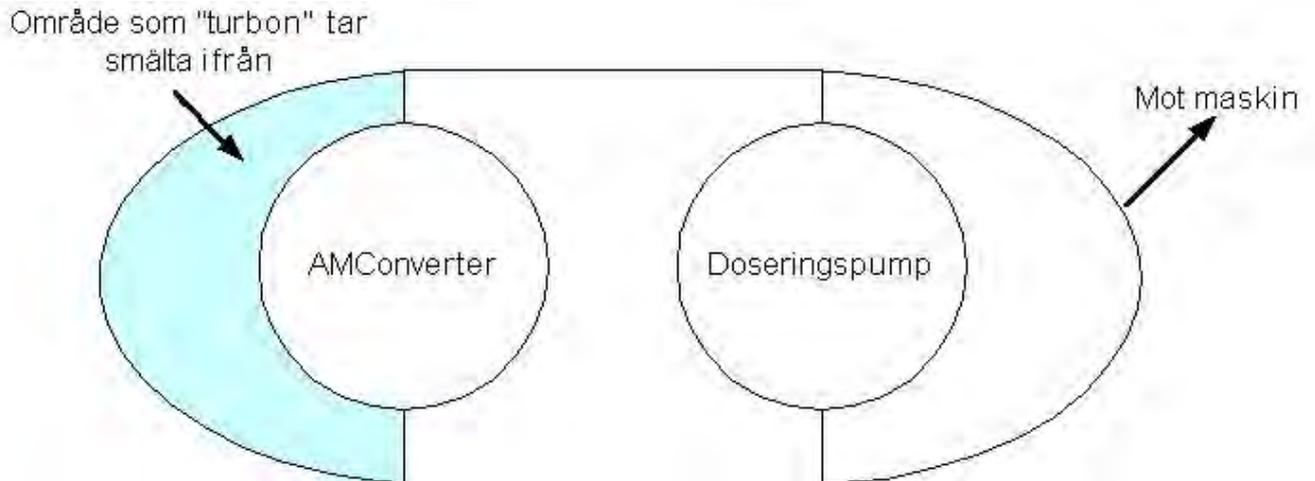


Figure 3: A schematic picture of where the converter was installed.

#### 2.1.1.2 The working principle of the AM-converter

A propeller is used to create a rotating flow of the melt. The melt floats through the propeller into the melt zone and goes out through openings near the melt surface. The solid metal, ingot or a recycled material, is lowered into this zone and melted under a constant melt flow, see *Figure 4*.



*The AM-converter before installation*



*The AM-converter incorporated in the furnace*



*The propeller, which rotate the melt*



*The melting zone where the materials are fed into the furnace*

*Figure 4: The construction of the AM-converter at Finnveden Gjtal AB.*

The main advantages with the method are [4]:

- A rapid melting sequence
- Maintenance of a uniform temperature
- Minimisation of the melt surface area that is disturbed when ingots and solid material are fed into the furnace.
- A separation of oxides which can be easily removed from the melt surface.

The AM-converter facilitates efficient melting of both ingots and returns with low melt losses.

### 2.1.1.3 Evaluation methods

The function of the AM-converter was evaluated by measuring how frequent a certain failure occurred.

The melt temperature was measured at six places in the furnace.

To measure the level of dross produced the weight of the dross skimmed from the surface during cleaning of the melt was compared to the total weight of melted material.

The composition from the ingot and the casted component was investigated by using spectrometry. This was done in order to secure that the material used in the AM-converter did not increase the level of deteriorating alloy elements. The analysis was done at Hydro Magnesium in Porsgrunn.

## 2.1.2 Result

During the test period totally 8 000 shots was made with the AM-converter installed into the furnace.

### 2.1.2.1 Production

The productivity was about 80 % during the test period. The main reason why the machine stopped was problem with dosing of the metal from the furnace to the shot sleeve. No stops were related to the AM-converter.

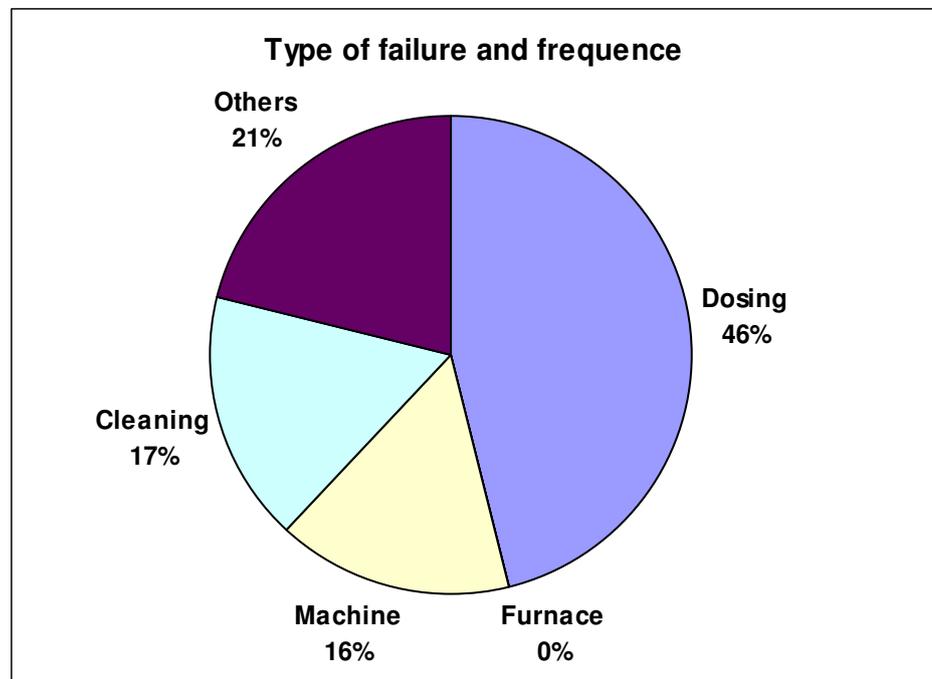


Figure 5: Stop frequencies and reasons during the test period.

There were some problems with the heating system inside the furnace during the start up of the furnace. This problem disappeared when using the AM-converter.

When the speed of the propeller was too high, this led to a build of a foam consisted of melt mixed with oxides.

During a five days period the level of dross produced was measured. The melt loss totalled 1 %, which is a low value. The working principle of the AM-converter makes oxides move to the top of the melt making cleaning and removal much simpler. Also, and due to the rapid melting, segregation of heavy particles causing bottom sludge is largely eliminated thereby making bottom cleaning a rare incidence.

There were much easier to melt down recycled material as biscuits and ingates than before. The build up of oxides was lower. Over 20 tonne scrap was melted during the test period.

### 2.1.2.2 *Material composition*

The spectrometry showed on a little increased level of the alloying elements Fe, Zn, Cu and Si. The values are though within the interval for the AM 50 standard.

The values in *Table 2* are mean values from 8 sparks on the component respectively 4 sparks on the ingot.

*Table 2: Material composition in the casted component and the ingots compared to the material standard for AM 50.*

	Al	Zn	Mn	Si	Fe (ppm)	Cu (ppm)	Ni (ppm)	Be (ppm)	Mg
<b>Standard</b>	<b>4,5-5,3</b>	<b>Max 0,20</b>	<b>0,28-0,50</b>	<b>max 0,05</b>	<b>max 40</b>	<b>max 80</b>	<b>max 10</b>	<b>-</b>	<b>rest</b>
<b>Component</b>	<b>4,83</b>	<b>0,065</b>	<b>0,35</b>	<b>0,043</b>	<b>13</b>	<b>51</b>	<b>6</b>	<b>2,8</b>	<b>94,7098</b>
Variance	0,18	0,004	0,006	0,004	2	5	1	0,5	0,1873
<b>Ingot</b>	<b>4,94</b>	<b>0,001</b>	<b>0,33</b>	<b>0,039</b>	<b>3</b>	<b>29</b>	<b>6</b>	<b>4,7</b>	<b>94,6833</b>
Variance	0,18	0,00	0,016	0,0013	2	2	1	0,7	0,1782

### 2.1.3 Discussion

The production test with the AM-converter turned out well. Finnveden Gjotal AB is today using the device in the ordinary production of magnesium. The main advantage has been an increased melt velocity, which resulted in a higher production capacity. This is also probably the reason why the furnace works better when using the AM-converter.

The working environment at the melt system was not satisfactory during the test period. The reason to this was that the operator had to manually feed the furnace. Because of the rapid melting this had to be done continuously. For the operator this involved working in a hot area under a long period performing non recommended ergonomic lifts and movements.

The steel used in the AM-converter has not resulted in an increased level of deteriorating elements. Before the test was made there was an apprehension that the movement of the melt around the AM-converter could lead to this.

Finnveden Gjutas AB had no problem with the melting of recycled material. The AM-converter made it much easier. When the rate of recycled material was too high this resulted though in an increased level of sludge and dross.

Seeing that bottom sludge comes up to the surface should also lead to a higher quality of the material in the component, because of a lower risk for that the sludge will be sucked into the dosing system.

Further work involves more research about:

- If the consumption of protection gas could be decreased?
- If the crucible life will be increased?
- How much the metal loss reduces under real production circumstances?

## 2.2 New type of cover gas for magnesium melt

To avoid a heavy exothermic reaction when melting magnesium, it is needed to protect the melt surface with a cover gas or salt. The cover gas act to change the characteristics of the oxide film so that it adheres well to the underlying molten magnesium, self-repairs when disturbed or broken, and provides effective protection form further oxidation. The choice of an effective cover gas system, together with efficient furnace closures and melt handling systems, enables molten magnesium to be handled without excessive oxidation or burning. The most common cover gas systems are SF<sub>6</sub> and SO<sub>2</sub>, but due to a high environmental load respectively high toxic inhibition works is done to find better replaceable gas systems. The use SF<sub>6</sub> will also be forbidden to use as a cover gas in the European Union 2007 according to the Kyoto agreement [5].

One activity in the project has been to investigate how much SF<sub>6</sub> the Swedish die casters are using and helping the Swedish Environmental Protection Agency to formulate new national regulations about the use of F-gases.

The Australian research organisation CAST has developed a new type of gas system called AM-cover. The system is commercialised by AM-technologies. The main active component in the gas system is the gas HFC-134a. The gas is normally used in air conditioning systems and has a considerably lower GWP value (GWP= Global Warming Potential). Die casters in Europe and USA have conducted several tests with AM-cover and the Swedish magnesium die casters are highly interesting to see if the gas could replace the current system.

To test AM-cover trials were conducted at Husqvarna AB during the period 2004-03-12 -- 2004-04-16. Involved people were Markus Blomdahl, Swedish Foundry Association, Ola Ring, Husqvarna AB, Simon Cashion, AM-technologies, Jan Bolstad, AM-technologies.



*Figure 6: The test was made at Husqvarna AB in collaboration with Swedish Foundry Association and Advanced Magnesium Technologies.*

## 2.2.1 Method

To evaluate the system it was important to compare the velocity of the oxidation process between the current gas system and AM-cover. The reaction was possible to measure by using an infrared camera.

The test was carried out in the following way:

1. The main lid on the furnace was opened.
2. By scraping of the oxide layer, the surface of the melt was cleaned.
3. The lid was held opened, so that the oxygen could react with the melt and build up a new oxide layer.
4. An infrared camera measured the process.
5. An computer program for IR-pictures was used to evaluate the process.

The test procedure was repeated at two times per gas system. The first measure was made at 12-03-2004 with Husqvarna's current system based on a mix of SF<sub>6</sub>, CO<sub>2</sub> and dry air. At 17-03-2004 this system was replaced by AM-cover and the effect was measured short after the change. AM-cover was then used in production until 16-04-2004. Before the test was ended another measurement was made. To compare the system with SF<sub>6</sub> a follow up measurement was made under the same condition as for the ending test with AM-cover. It is important to emphasise that the tests were conducted under real production condition in a combined melting and holding furnace.

The conditions during the test is presented in *Table 3*. One important factor that was different between the test occasions was the melt temperatur, which was about 10 °C higher during the ending test. The gas flow was about the same for all tests.

*Table 3: Test parameters for the four measurements that were made.*

<b>Trial parameters</b>	<b>Meas 1: SF<sub>6</sub></b>	<b>Meas 2: AM-cover</b>	<b>Meas 3: AM-cover</b>	<b>Meas 4: SF<sub>6</sub></b>
<i>Alloy</i>	<b>AZ91</b>	<b>AZ91</b>	<b>AZ91</b>	<b>AZ91</b>
<i>Beryllium</i>	<b>11 ppm</b>	<b>8 ppm</b>	<b>5 ppm</b>	<b>5 ppm</b>
<i>Melt temperature</i>	<b>690 °C</b>	<b>690 °C</b>	<b>700 °C</b>	<b>700 °C</b>

To analyse the build up of an oxide layer a heat camera was used. This could be done, because that the emissivity for a cleaned melt surface compared to an oxide layer differ largely. The value of the emissivity can differ from 0,1-1.0.

$$\text{emissivity} = \frac{\text{transmission from the surface of the object}}{\text{transmission from a black body}}$$

Figure 7: The formula for calculation of the emissivity

The shinier the surface is, the lower is the value of the emissivity. When taking an infrared picture it is important to know and use the right value of the emissivity, which is manually adjusted in the camera settings. If you are using a higher value this leads to that a lower temperature will be showed. Through looking at the pictures it was obvious that this change of the real emissivity appeared when the showed melt temperature was about 550 °C, when using an emissivity value of 0,95. To be able to compare and analyse the measurements a formula was constructed in the computer program for IR-pictures. The formula calculates how many percent of a fixed area that have a temperature over 550 °C. To better visualise the reaction an isotherm is used, which colours every pixel red that has a temperature over 550 °C.

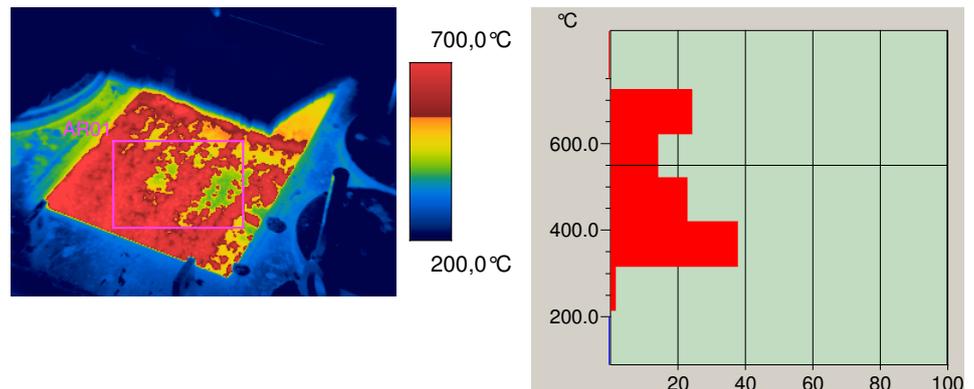
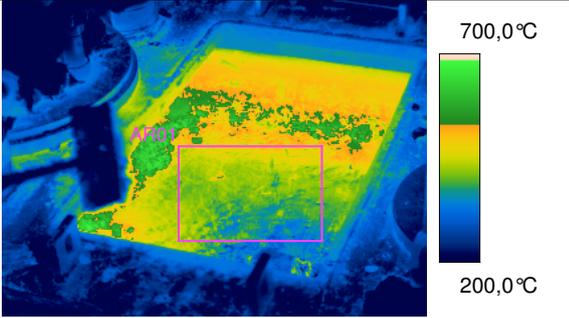
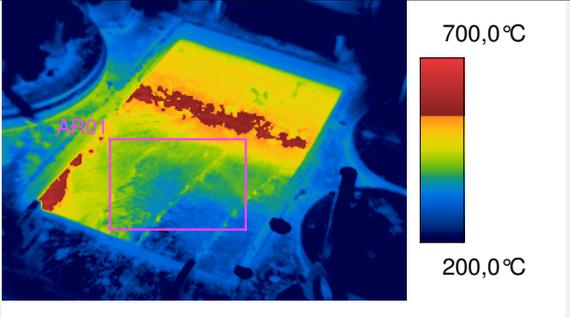
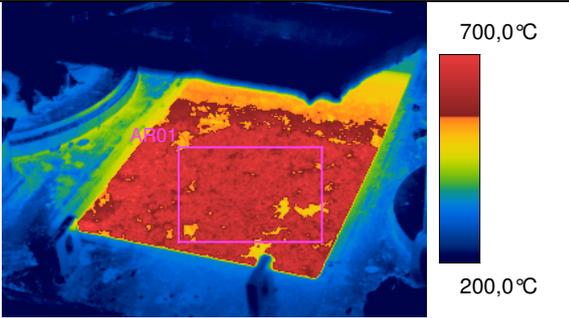
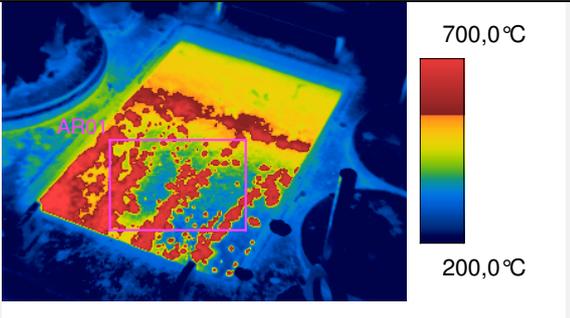
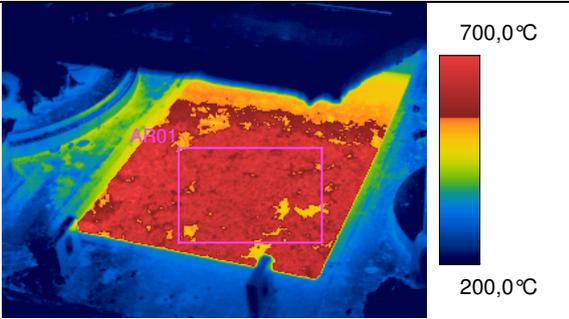
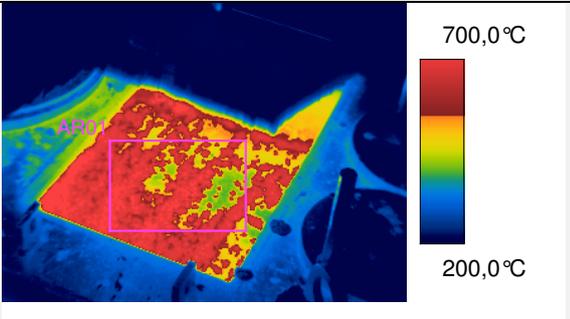


Figure 8: The left pictures show how the fixed area was placed. The red colour is an isotherm that visualises when the temperature is over 550 °C. The right pictures shows the distribution of the temperature inside the fixed area.

## 2.2.2 Results

The results from the test are showed below. In *Figure 9* the opening tests are presented. The SF<sub>6</sub>-system is showed to the left and the AM-cover to the right. To be able to compare the systems the pictures are taken at the same time during the test. In *Figure 10* the ending tests are presented by the same way.

<b>Start</b>	
9.39:39 - 12/3	14.41:36 - 17/3
<b>Test 1: SF<sub>6</sub></b>	<b>Test 2: AM-cover</b>
 <p>Thermal image of the SF<sub>6</sub> system at the start of the test. The melt area is highlighted in yellow and green, indicating temperatures between 200,0°C and 700,0°C. A pink box labeled 'AR01' is visible on the melt surface. A color scale on the right ranges from 200,0°C (blue) to 700,0°C (red).</p>	 <p>Thermal image of the AM-cover system at the start of the test. The melt area is highlighted in yellow and green, indicating temperatures between 200,0°C and 700,0°C. A pink box labeled 'AR01' is visible on the melt surface. A color scale on the right ranges from 200,0°C (blue) to 700,0°C (red).</p>
<b>Melt after 2 minutes</b>	
9.41:36 - 12/3 <b>(The trial ends)</b>	14.43:36 - 17/3
<b>Test 1: SF<sub>6</sub></b>	<b>Test 2: AM-cover</b>
 <p>Thermal image of the SF<sub>6</sub> system after 2 minutes. The melt area is now predominantly red, indicating temperatures near 700,0°C. A pink box labeled 'AR01' is visible. A color scale on the right ranges from 200,0°C (blue) to 700,0°C (red).</p>	 <p>Thermal image of the AM-cover system after 2 minutes. The melt area is predominantly red, indicating temperatures near 700,0°C. A pink box labeled 'AR01' is visible. A color scale on the right ranges from 200,0°C (blue) to 700,0°C (red).</p>
<b>Melt after 2 minutes 34 seconds</b>	
9.41:36 - 12/3 <b>(The trial is ended)</b>	14.44:24 - 17/3 <b>(The trial ends)</b>
<b>Test 1: SF<sub>6</sub></b>	<b>Test 2: AM-cover</b>
 <p>Thermal image of the SF<sub>6</sub> system after 2 minutes 34 seconds. The melt area is predominantly red, indicating temperatures near 700,0°C. A pink box labeled 'AR01' is visible. A color scale on the right ranges from 200,0°C (blue) to 700,0°C (red).</p>	 <p>Thermal image of the AM-cover system after 2 minutes 34 seconds. The melt area is predominantly red, indicating temperatures near 700,0°C. A pink box labeled 'AR01' is visible. A color scale on the right ranges from 200,0°C (blue) to 700,0°C (red).</p>

*Figure 9: The opening measurements made for SF<sub>6</sub> (left) and AM-cover (right). The melt temperature was about 690 °C.*

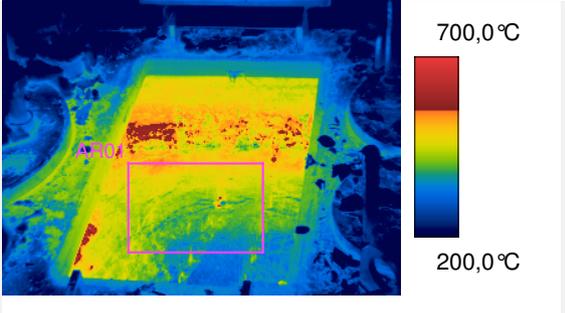
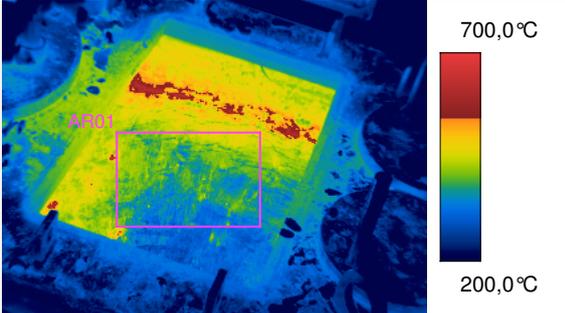
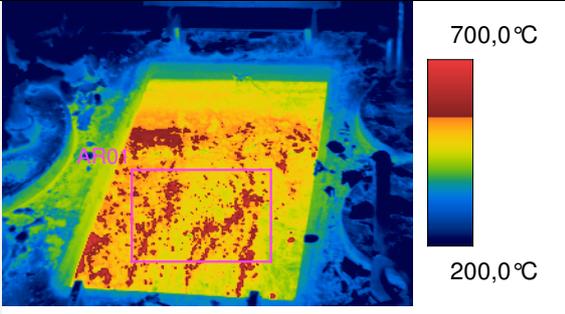
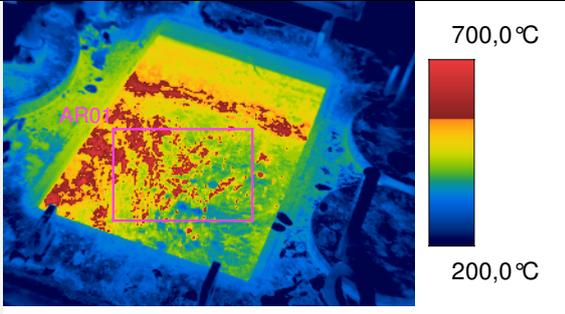
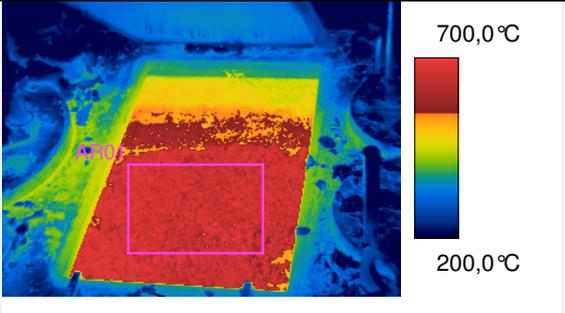
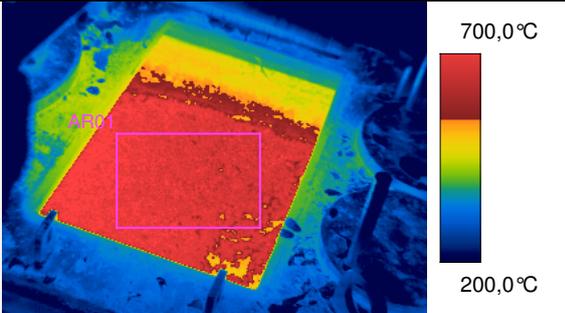
<b>Start</b>	
15.39:28 - 16/4	13:45.05- 16/4
<b>Test 4: SF<sub>6</sub></b>	<b>Test 3: AM-cover</b>
	
<b>Melt after 40 seconds</b>	
15.39.57 - 16/4	13:45.31- 16/4
<b>Test 4: SF<sub>6</sub></b>	<b>Test 3: AM-cover</b>
	
<b>Test end</b>	
<b>The trial ends after 1min 12 seconds</b> 15.40.40- 16/4 - test 1	13:46.31- 16/4 <b>The trial ends after 1 minute and 40 seconds</b>
<b>Test 4: SF<sub>6</sub></b>	<b>Test 3: AM-cover</b>
	

Figure 10: The ending measurements made for SF6 (left) and AM-cover (right). The melt temperature was about 700 °C.

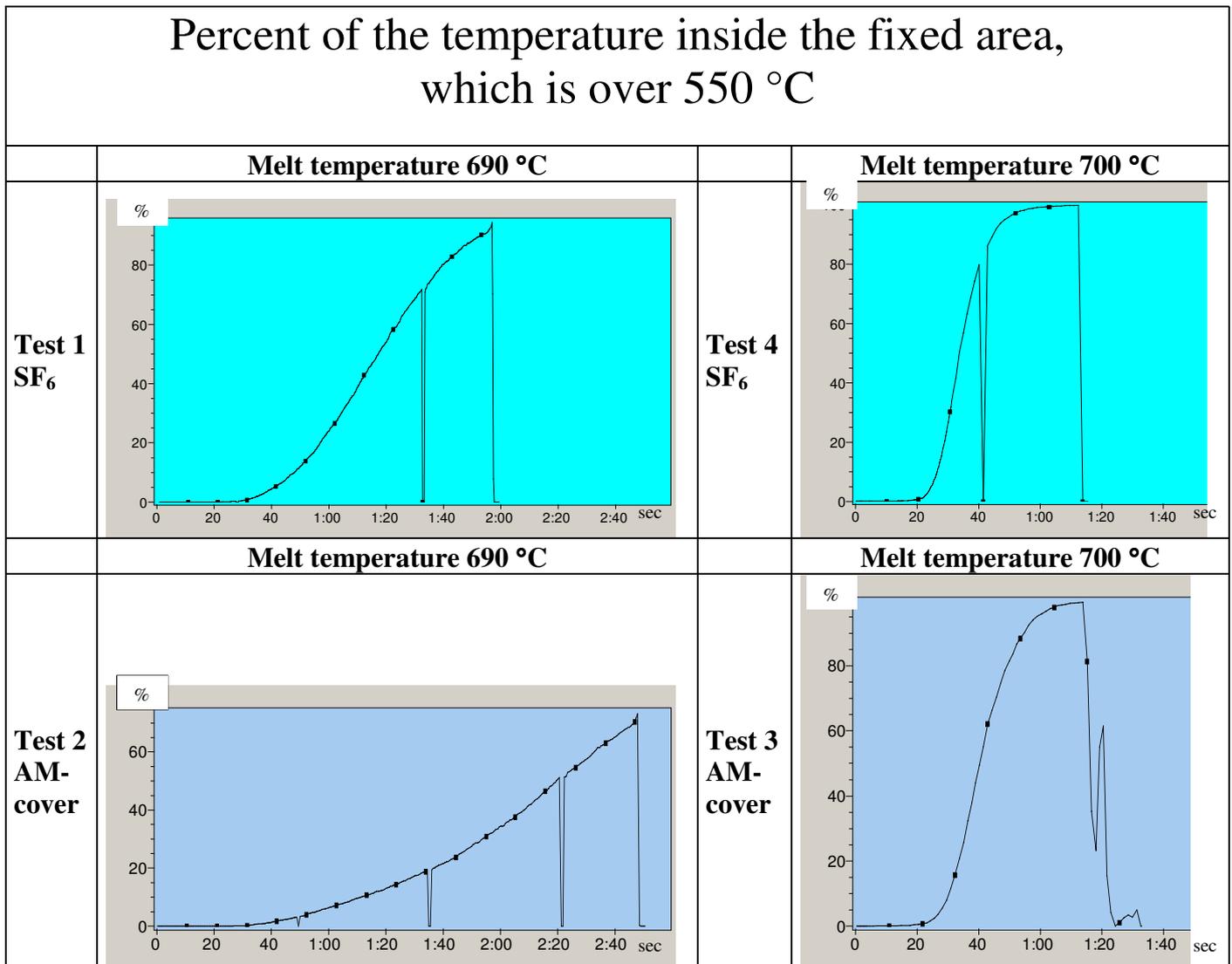


Figure 11: The diagrams show the distribution of the temperature inside the fixed area, which is over 550 °C. The longer time it takes to reach 100 %, the better is the gas systems ability to protect the melt.

By looking at the diagrams in Figure 11 is it possible to compare the reaction from a cleaned surface until it is totally covered with an oxide layer. The diagrams show the distribution of the temperature inside the fixed area, which is over 550°C, expressed as a percentage. The longer time it takes to reach 100 %, the better is the ability of the gas systems to protect the melt. The tests made at 690° C was ended before the whole area was covered with an oxide layer, see especially test 2 in Figure 11.

### 2.2.3 Discussion

By looking at the results from the tests the following statements can be done.

- **AM-cover gives improved protection of the melt compare to a SF<sub>6</sub>-system.**
  - Longer time for the build up of the oxide layer.
  - A less amount of HFC-134a was actually used in the test.
- **A higher melt temperature and a low content of beryllium have a large effect on the function of the gas-systems.**
  - The reaction time is considerable faster at the ending test, when the melt temperature is higher and the content of beryllium lower. This applies for the both gas systems.
- **Much lower environmental load with AM-cover**
  - up to 95 % lower Global Warming Potential (GWP).

The tests show that AM-cover can replace SF<sub>6</sub>. Before this is done it is though important to work with following questions.

- A total cost analyse has to be done looking at the gas consumption, metal loss, build up of dross and sludge.
- Optimise the flow and concentration of AM-cover for the specific melt process and also test different gas mixes
- Make more tests about how the melt reacts outside the furnace.

## 2.3 Testing the robustness of the casting process

To be able to achieve a cost effective production of die casted magnesium components, it is of highest importance to understand how different process parameters influences the origin of defects and the final quality of the component. Reducing the rejection rates will lead to a higher productivity, a lower environmental load and lower energy consumption.

Common causes, why components are rejected, are porosities, cold flows and hot tears. This study comprises robustness testing of a components made of AM 50, where the main focus are how the machine setting affect the formation of hot tears. To the best knowledge of the authors, no reports are available in the literature concerning the influence of process parameter settings on the hot tearing tendency of high pressure die casted magnesium components [6].

The studies were carried out by Haiping Cao, Jönköping University, Magnus Wesén, Jönköping University, Joakim Karlsson, Finnveden Gjotal AB, Niclas Thulin, Husqvarna AB, Mattias Östklint, Husqvarna AB, Dan Jacobsson, KIMAB and Petter Kylefors, Scania CV AB.

### 2.3.1 Method

A full factor experimental plan was created. By changing one factor per setting the experiments were done. It was assumed that the following parameters have the most influence of the build up of defects:

- Casting temperature
- Phase 1, velocity
- Phase 2, velocity
- Phase 2, starting point
- Intensification pressure
- Mould opening time

All the specimens were inspected by using a liquid penetration technique to reveal any existence of surface defects such as hot tears, cold flows etc. The penetrant testing was done in three steps:

- (1) application of penetrant liquid on the thoroughly cleaned surface for about 10 minutes,
- (2) removing the excess penetrant liquid,
- (3) application of a thin layer of developer to the surface. The indications of surface tears appeared soon after applying the developer.

Metallographic analysis was also carried out on specimens taken from areas where hot tears frequently formed, in order to have more detailed information about the characteristics of microstructure in the tear regions.

To investigate how different internal defects are distributed in the components some of them have been x-rayed.

By using a tension test machine it has been possible to see how the process variations had affected the mechanical properties.

A large plate-like component with some strengthening ribs was die casted using AM50 with various process parameter settings. The experiments were made in an IDRA 2 750 tonne cold chamber die casting machine having a shot sleeve length of 820 mm. *Table 4* lists the various different process parameter settings studied during the experiments. In order to achieve relatively stable casting conditions, the first 10 shots of each parameter setting were discarded, after which another 4 shots were collected for further analysis. Altogether, 48 castings from the 12-parameter settings were produced and analysed.

Table 4: Experimental plan for test with an AM-50 component. The blue dots means that these samples are mechanical tested. The green dots means that the samples have been x-rayed.

No.	Casting Temperature (°C)	Phase1 Velocity (m/s)	Phase2 Velocity (m/s)	Phase2 Start (mm)	Intensification Pressure (bars)	Mould Opening time after Injection (s)	Fullness of sleeve (%)
1	Normal	Normal	Normal	Normal	Normal	Normal	Normal
2	normal	Slow	normal	normal	normal	normal	normal
3	normal	High	normal	normal	normal	normal	normal
4	normal	normal	Slow	normal	normal	normal	normal
5	normal	normal	High	normal	normal	normal	normal
6	normal	normal	normal	Early	normal	normal	normal
7	normal	normal	normal	Late	normal	normal	normal
8	normal	normal	normal	normal	Low	normal	normal
9	normal	normal	normal	normal	high	normal	normal
10	normal	normal	normal	normal	normal	Short	normal
11	normal	normal	normal	normal	normal	Long	normal
12	normal	normal	normal	normal	normal	normal	Low

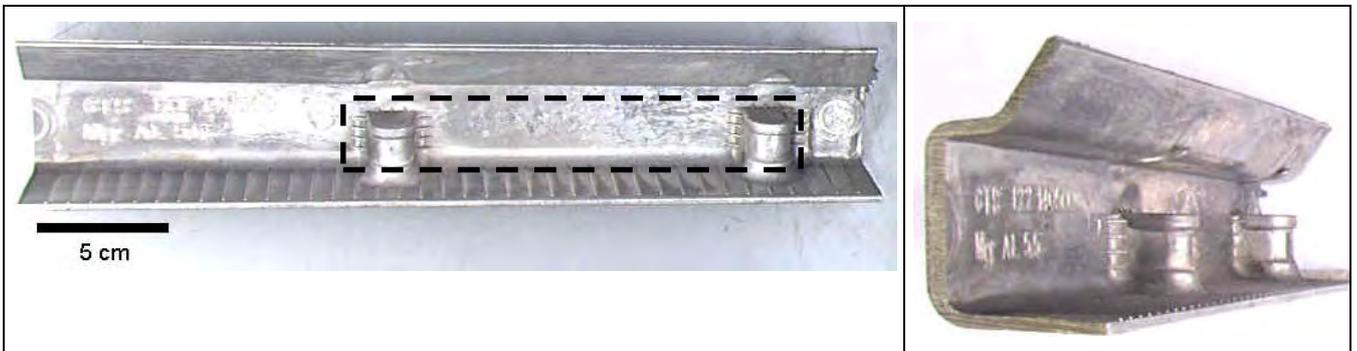


Figure 12: Specimens for tension tests has been taken from the marked area in the left picture.

### 2.3.2 Results

Casting temperature and phase I velocity were found to have no detectable effect on the hot-tearing tendency in these experiments. However, all other process parameter settings were found to have some effect.

Table 5: Effects from different process parameter settings

• Phase 2 plunger velocity	Faster velocity decreased the hot-tearing tendency.
• Phase 2 start position	Delaying the start position increased the hot-tearing tendency.
• <b>Mould opening time</b>	Longer time from filling the cavity until the die is opened increased the hot-tearing tendency.
• Intensification pressure	A high pressure increased the hot-tearing tendency.

By using the penetration inspection method it was possible to visualise the hot tears. The method was successful for detecting defects when process parameters as velocity and starting point of the second phase and the mould opening time was changed.

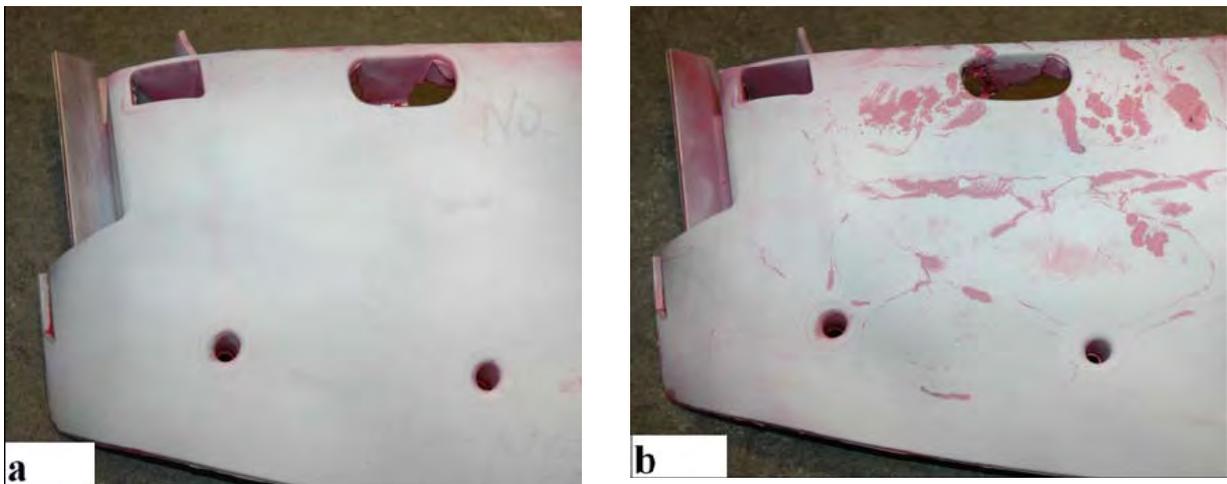


Figure 13: Penetration inspection results of specimens cast at:  
 a)  $start_{II} V = 520 \text{ mm}$ , b)  $start_{II} V = 725 \text{ mm}$

For changes made during the second phase, the hot tears had a high amount of the brittle  $\alpha/\beta$  eutectic close to the tear edges, see Figure 14.

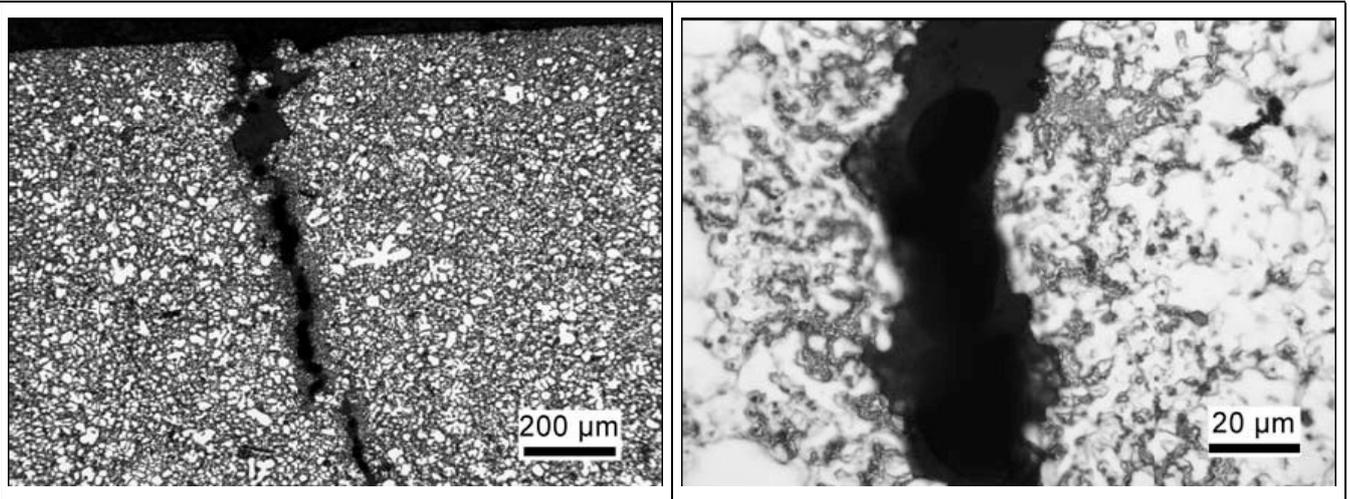


Figure 14: Typical morphology of hot-tearing areas in specimens cast with late phase II start, at low and high magnification.

Especially when using the slower second phase velocity, the hot-tears where located close to the rib regions. When the starting point was delayed this also led to other surface defects.

The formation of hot-tears because of a longer mould opening time had no  $\alpha/\beta$  eutectic inside it.

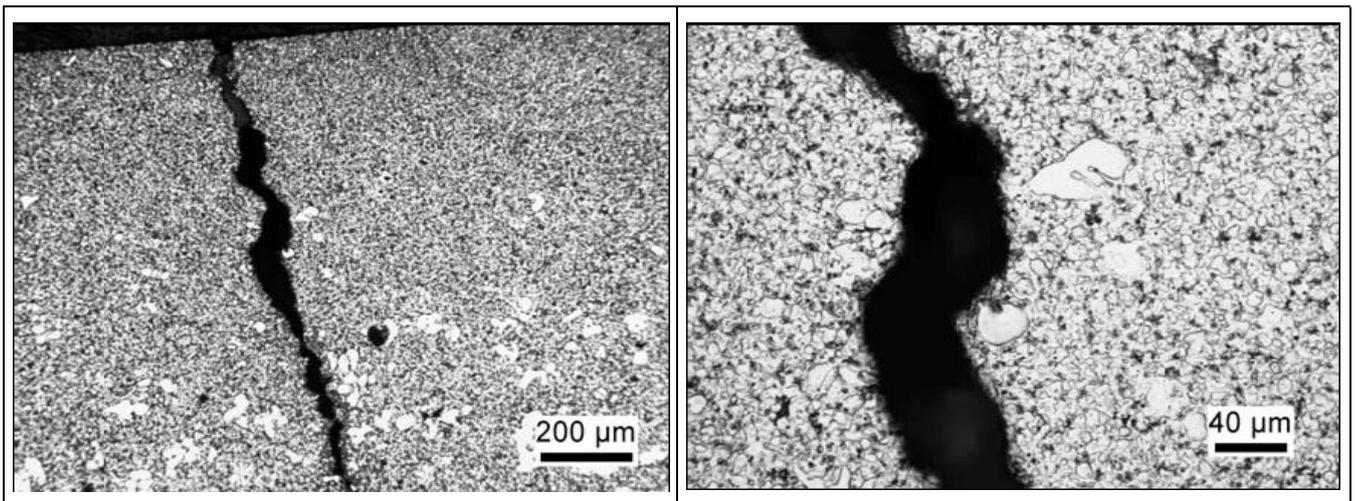


Figure 15: Typical microstructure of hot-tearing areas in specimens cast with a long mould opening time,  $open\ t = 7.5\ s$ , at low and high magnification.

A higher intensification pressure normally is used when it is needed to feed the component with metal during the solidification and to minimise the size of the porosities. It can also decrease the formation of segregation bands. In this experiment it was found that a higher pressure cause hot-tears to form. Because of the higher pressure the hot-tears was sometimes totally filled with  $\alpha/\beta$  eutectic and in that case the defects was hard to find.

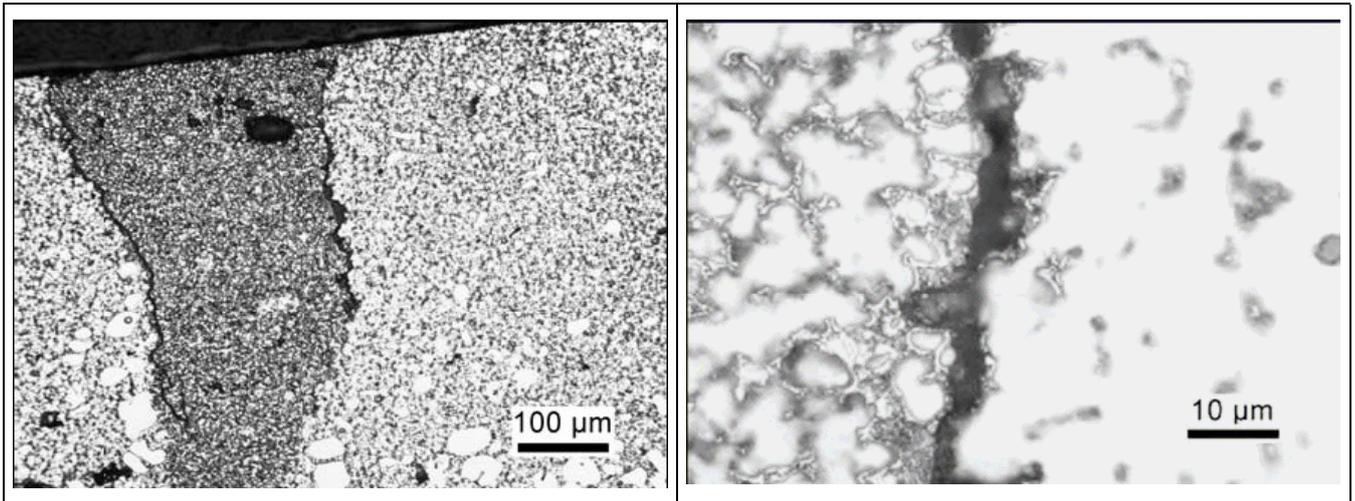


Figure 16: Typical microstructure of hot-tearing areas showing tearing in specimens cast with high intensification pressure,  $int P = 280$  bars, at low and high magnification.

The x-ray inspection showed a considerable amount of internal defects when using a slow velocity of the first phase and a high intensification pressure. For the other parameter settings the amount of defects was lower and the distribution more general. In order to better classify the type of defects some samples were cut out from the component and polished. A computer programme for picture analysis was used to determine the level of porosities.

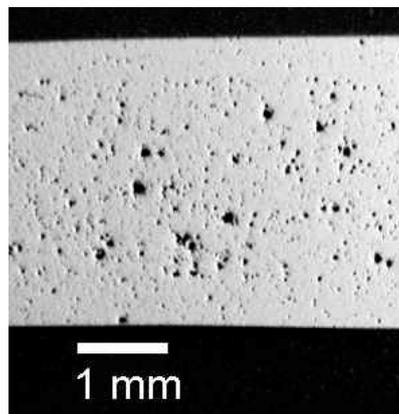


Figure 17: Polished surface from sample 12-2. The porosity level was measured to 3,25 %.

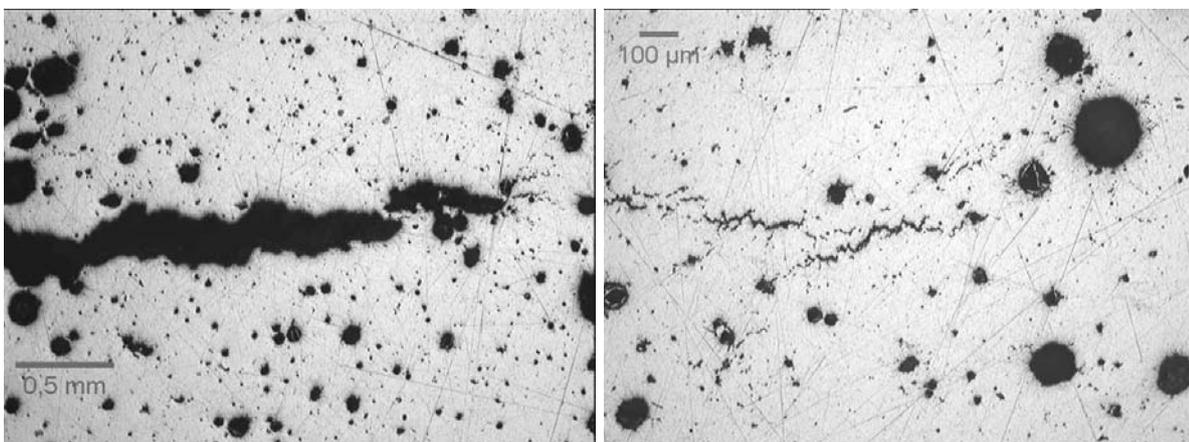


Figure 18: Hot tears in sample 9-1. The one to the left is more opened.

To test the mechanical properties samples were manufactured from the component and tested in a tension test machine. The variance is in general small between the samples. Two samples discern from the others and those are sample 9 and 10. The yield strength is lower compare to the others, but both the ultimate strength and the true strain are the highest for sample 10. No defects other than porosities could be detected in that sample.

Table 6: Results from the mechanical testing of AM 50 component.

Sample	Yield strength [MPa]	Ultimate strength [MPa]	Strain [%]	Level of porosity [%]
1-1	120	195	6,6	5,62
1-2	118	193	6,6	4,47
1-3	120	187	6,2	3,67
1-4	118	188	5,8	4,62
2-2	118	186	5,9	4,65
3-1	119	196	6,9	3,69
3-2	117	193	6,5	3,23
4-1	120	197	6,7	3,07
4-2	118	188	6,0	2,55
5-1	119	196	7,0	4,49
5-2	119	200	7,4	3,3
9-1	111	169	4,4	4,89
9-2	107	155	3,8	3,3
9-3	105	144	2,9	3,1
9-4	113	170	4,8	3,73
10-2	111	211	9,4	5,38
12-1	120	201	7,1	4,68
12-2	116	206	8,1	3,25
<b>Mean value</b>	<b>116</b>	<b>188</b>	<b>6,2</b>	<b>4,0</b>
<b>Standard deviation</b>	<b>4,7</b>	<b>17,0</b>	<b>1,5</b>	<b>0,9</b>

Compared to the standard values for AM 50, the measured values are within the allowed interval.

Table 7: Standard values for AM 50 compared to the measured.

	Yield strength [MPa]	Ultimate strength [MPa]	Strain [%]
Measured	105-123	144-211	1,8-9,4
Measured, no defects*	111-123	186-211	4,8-9,4
EN-MC21220	110-130	180-230	5-15
ASTM AM50A	125	210	10

### 2.3.3 Discussion

One well-known method to decrease the hot tearing tendency is to avoid large temperature variations throughout the casting. Large temperature variations normally lead to localised areas of thermally induced high stresses, which finally can cause hot tears to form. Bearing this in mind, it is not difficult to understand that an increased phase II velocity (or cavity filling velocity) decreased the hot tearing tendency. A high filling velocity, and consequently a short filling time, will give rise to smaller temperature differences within the casting immediately after cavity filling. The importance of temperature variations was further emphasised by the heavy tearing formed in the specimens cast at a late phase II starting point; see Fig. 3b. The late phase II start caused some pre-filling of the cavity during the slow shot phase (phase I). The pre-filled liquid had spent a relatively long time inside the cold mould cavity before the fast shot phase started, and it is likely that a considerable amount of solid had formed during this time. This would certainly result in large temperature differences and concomitantly large hot tearing tendencies. The less significant effect of casting temperature and phase I velocity further emphasises that the cavity filling sequence is what is most important for the formation of hot tears.

It was observed that a longer mould opening time resulted in more severe hot tear formation. This can be explained by the tensile stresses, which build up while the casting stays inside the mould. The tearing morphology in *Figure 15* indicates that the tear has formed at the very end of solidification, or even below the solidus temperature, since no segregated eutectic could be observed inside the tearing region. This is in contrast to the tear morphologies observed when casting with a low phase II velocity or with a late phase II start point. The high amount of eutectic in the material adjacent to these tears indicates that they formed during the later stages of the solidification, and that a segregated liquid has initially flowed into the opening tears. Due to the solid and liquid shrinkage, the tears thereafter have widened up when no more segregated liquid could be fed to the tear region.

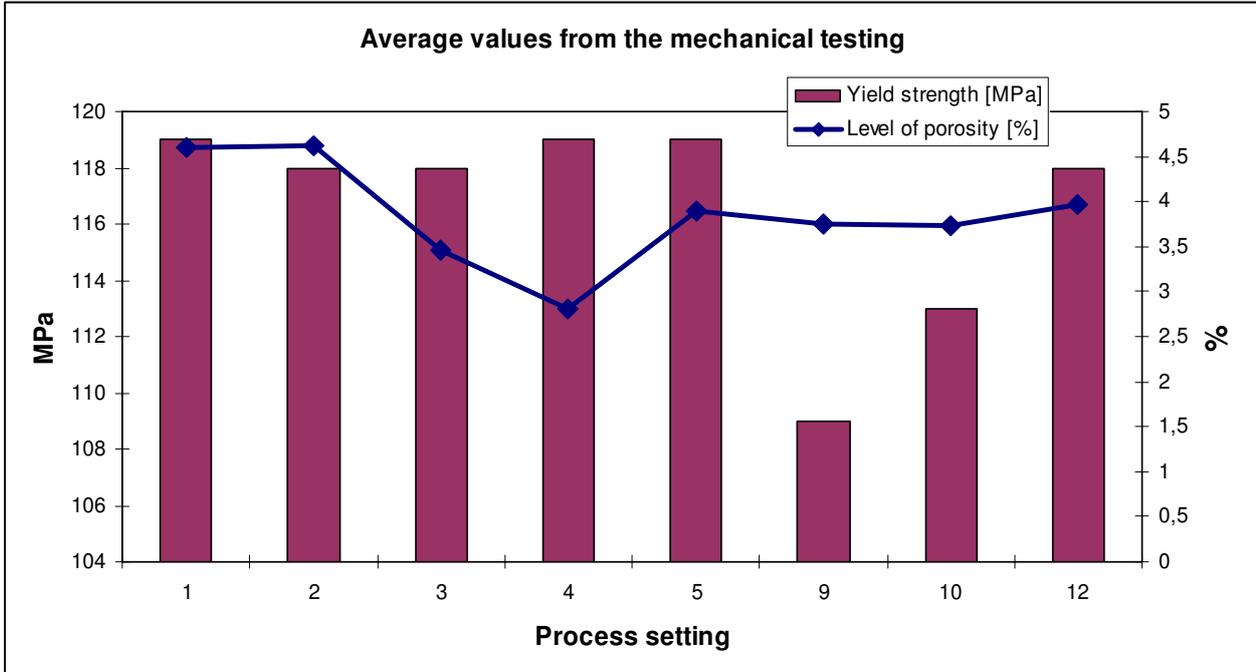
It was found that a high intensification pressure resulted in more severe hot tear formation, but also that the tears were sometimes completely filled with eutectic liquid; thereby making it practically impossible to detect the “tears” without sectioning and metallographically investigating the castings, see *Figure 16*. According to our numerical calculations, a component cast at a higher intensification pressure will have higher temperature gradients as well as higher solid fraction gradients between the surface and the centre during solidification. This situation will facilitate the initiation of cracking and further flow of segregated liquid into the opening tears.

The following testing showed that difference process settings had small or no influence on the mechanical properties or on the amount of porosities in general.

The internal defects as porosities were found to increase when using a low filling grade and a high intensification pressure. The increased amount of

porosities comes not surprisingly. It is well known that that the filling process of the shot sleeve during first phase can affect the amount of trapped air in the melt.

No correlation between the level of porosities or the yield strength could be found, see *Figure 19*. There was also no correlation between the differences in the thickness of the component to the yield strength.



*Figure 19: Diagram that shows the average value for samples from the different process settings, that was investigated through mechanical testing.*

## 2.4 Recycling of magnesium

All commonly used die-casting magnesium alloys can be recycled. The magnesium scrap is categorised into several types depending on how clean and dry it is, how much oxide there are and the size of it. Biscuits, ingate and venting systems, which come directly from the production, is the easiest to recycle. Machining chips, flash, overflows, dross and sludge will contain higher quantity of oxides and require special precautions during recycling. Some die casters send all their scrap to specialised recycling companies, who can recycle all type of scrap. To make die casting of magnesium cost and environmental effective is it important that the casters learns how to in-house recycle as much material as possible. This will not only save money in reduced cost for the material, but will also reduce the transportation cost, because of a smaller need of in and out transports of new material and scrap.

In the project a model was developed to see what effect parameters as melt loss and rejection rates have on the energy consumption and the need of melted material. To visualise it, the model is presented as a flowchart. *Figure 20* shows an example made by the following parameters.

- Melt loss = **1 %**
- Casting rejection = **5 %**
- Trimming rejections = **2 %**
- Machining rejections = **2 %**
- Inspection rejections = **1 %**
- Ingate and overflows = **30 %** of the shot weight
- Machining = **1 %** of the component

To produce ten thousand 8 kg-components under the mentioned conditions, about 129 tonne has to be melted. Totally 49 tonne will be rejected, trimmed or machined of. About 46 tonne of it can be used in-house recycling system.

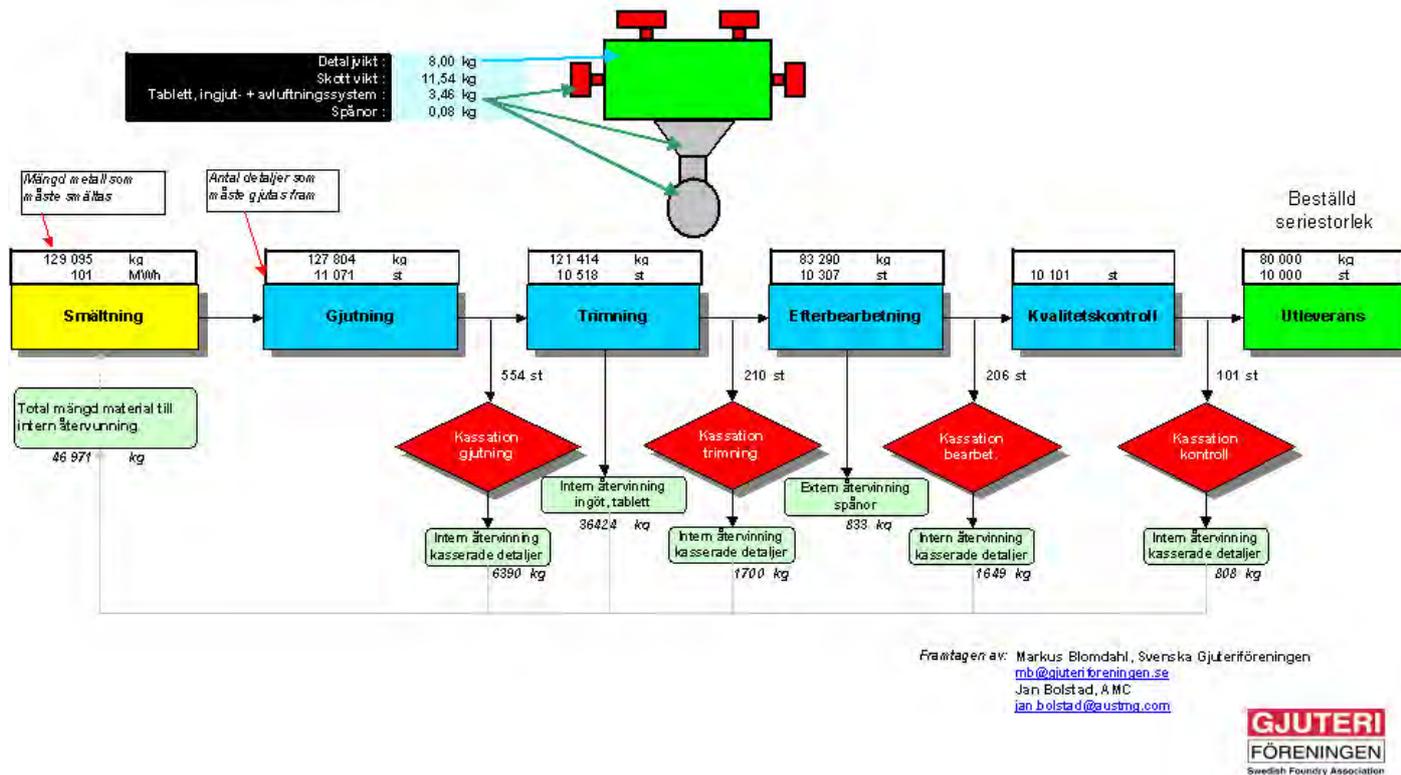


Figure 20: A flowchart presenting the result from the model, which shows how much energy and material that is needed to produce 10 000 components.

It is a considerable amount of material that can be in-house recycled. The current recommendation is that this should be avoided, because of a high capital cost for equipment to insure the right quality of the material.

Husqvarna AB recycle today all of their rejected parts, biscuits and ingate systems. One important question for them is how the melt quality is affected by total recycle rate. To test this an experiment was set up, where 100 % ingot respectively 100 % recycled material was melted and analysed. The main focus was to see how the level of oxides and the chemical composition was influenced by the rate of the recycled material.

Ola Ring, Husqvarna AB, Mattias Östklint, Husqvarna AB, Markus Blomdahl, Swedish Foundry Association, Petter Kylefors, Scania CV and Dan Jacobsson, KIMAB carried out the test.

## 2.4.1 Method

### 2.4.1.1 The melt system

The system is build up by two separated furnaces, one for melting the magnesium and one to hold the melt. The melt is transported between the furnaces via a transferring tube. Both salt and SF<sub>6</sub> are used to protect the melt to react with oxygen. A new system is used to charge the melt with preheated ingots. The recycled material is transported into the melting furnace by a conveyer belt and is only preheated by the hot air from the furnace.

Table 8: Data for the melt system at Husqvarna AB

	Size	Capacity	Melt protection
<b>Melting furnace</b>	1 700 kg	250 kW	SF <sub>6</sub> and salt
<b>Holding furnace M 11</b>	600 kg	90 kW	SF <sub>6</sub>
<b>Holding furnace M 15</b>	600 kg	90 kW	Salt
<b>Holding furnace M 22</b>	600 kg	90 kW	Salt

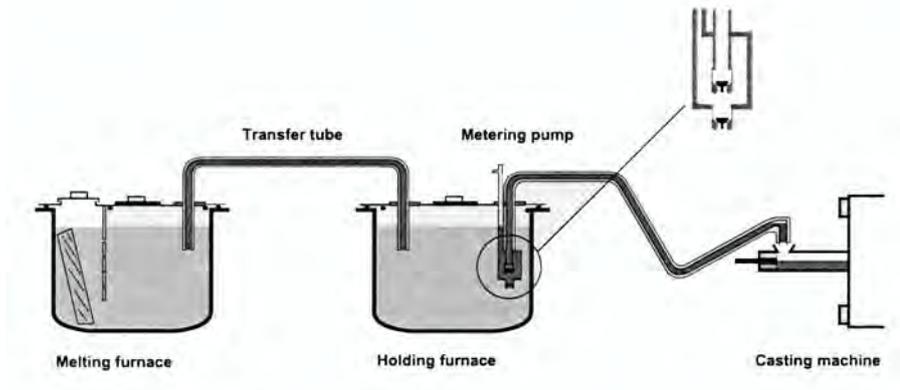


Figure 21: A schematic picture of the melt system

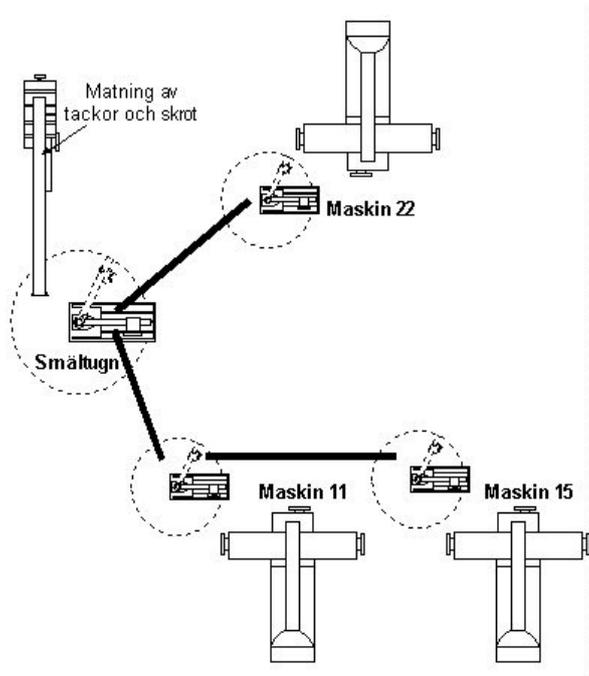


Figure 22: The set up of machines. Components were taken from machine 22 and 11. A HMIAM test was made at the melting furnace.



Figure 23: The charge system. To the left is the preheating and charging system and to the right is the conveyer belt filled with recycled material.

#### 2.4.1.2 The condition of the melt before measuring

Before it was possible to make any measuring, it was important that the melt consisted of 100 % ingots or 100 % recycled material. To guarantee the condition of the melt, the system was run for about 24 hours with the specific material that was ought to be measured.

Table 9: Test information (100 % ingots).

<b>Start up time</b>	2004-12-14; time 14.30
<b>Ending time</b>	2004-12-15 , time16.00
<b>Volume of melted material from start to end</b>	Approximately 8 tonne
<b>Material</b>	Ingots from Hydro Magnesium and Gold River
<b>Temperature inside the melting furnace</b>	Melting zone = about 680 °C Holding zone = 700 °C

Table 10: Test information (100 % recycled material).

<b>Start up time</b>	2004-12-15, time 16.00
<b>Ending time</b>	2004-12-16, time 15.00
<b>Volume of melted material from start to end</b>	Approximately 6 tonne
<b>Material</b>	Mixed magnesium scrap, mostly biscuits and ingates
<b>Temperature inside the melting furnace</b>	Melting zone = 670-708 °C Holding zone = 700 °C

### 2.4.1.3 *Norsk Hydro's Inclusion Assessment Method*

By using Norsk Hydro's Inclusion Assessment Method (NHIAM), was it possible to measure the level of oxides and intermetallic particles in the melt. The procedure for the method is roughly described below.

1. The steel container is lowered into the melt.
2. The vacuum is put on
3. The melt is sucked into the steel container through a filter until the container is partly filled. This takes about 10 minutes.
4. The vacuum is then switched off and the container is taken up from the melt.
5. The container is weight before and after the test. The difference shows how much melt that has floated through the filter.
6. The filter cake that is build up inside the filter cup is then analysed.

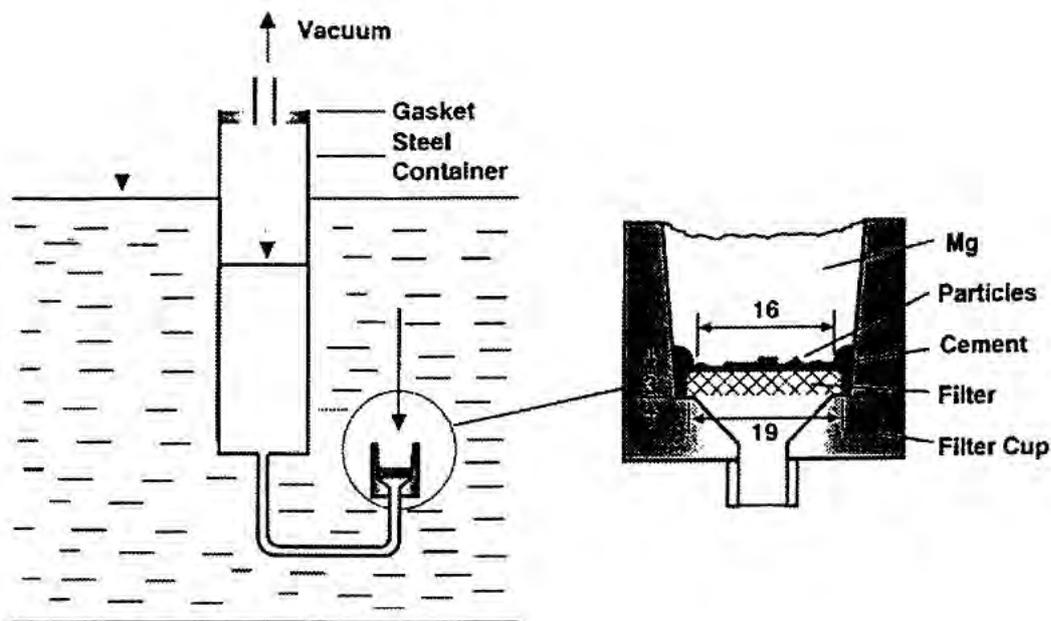


Figure 24: A schematic picture of the equipment for NHIAM [ 7].

### 2.4.1.4 *Analysis of the composition of the material*

Three different methods were used to analyse the composition of the material. At Husqvarna AB a normal spectrometer was used. At KIMAB a ICP-TOFMS (Inductively Coupled Plasma Time Of Flight Mass Spectrometry) method was used to identify Cu, Ni and Fe and to identify Mn, Zn and Al flame technical AAS was used.

Specimens were taken from components.

## 2.4.2 Results

## 2.4.2.1 Results from the material analysis

Table 11: Analysis of the composition of the material (100 % ingots)

	Al	Zn	Mn	Si	Fe	Cu	Ni	Be	Mg
<b>Charge</b>	9,1	0,69	0,218	0,031	0,0023	0,0017	0,0005	0,0010	Rest
<b>Component (Hsq)</b>	9,040	0,706	0,219	0,0371	0,0067	0,0080	0,0024	0,0003	
<b>Component (KIMAB)</b>	8,50	0,348	0,208		<0,0003	0,0014	0,00018		
<i>Standard deviation</i>	<i>0,14</i>	<i>0,010</i>	<i>0,004</i>			<i>0,0003</i>	<i>0,00005</i>		

Table 12: Analysis of the composition of the material (100 % recycled material)

	Al	Zn	Mn	Si	Fe	Cu	Ni	Be	Mg
<b>Component (Hsq)</b>	8,873	0,762	0,228	0,0289	0,0080	0,0042	0,0018	0,0003	
<b>Component (KIMAB)</b>	8,27	0,345	0,185		<0,0003	0,0015	0,00018		
<i>Standard deviation</i>	<i>0,12</i>	<i>0,006</i>	<i>0,004</i>			<i>0,0002</i>	<i>0,00003</i>		

### 2.4.2.2 Results from the NHIAM filter test

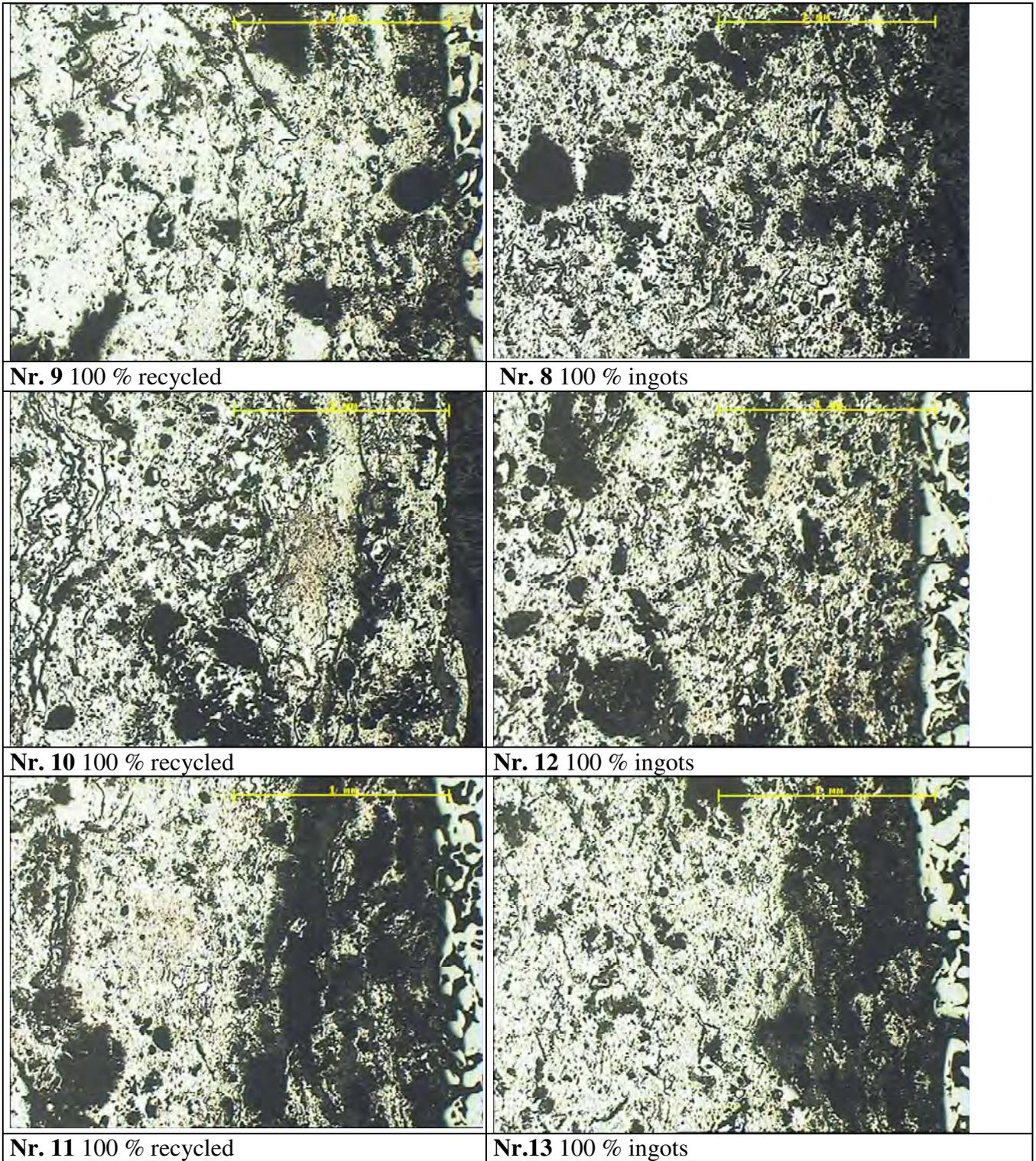


Figure 25: Pictures of the filter cake using NHIAM

### 2.4.2.3 Mechanical properties

Seven components were taken out for mechanical testing in order to see if the recycling rate affects the mechanical properties.

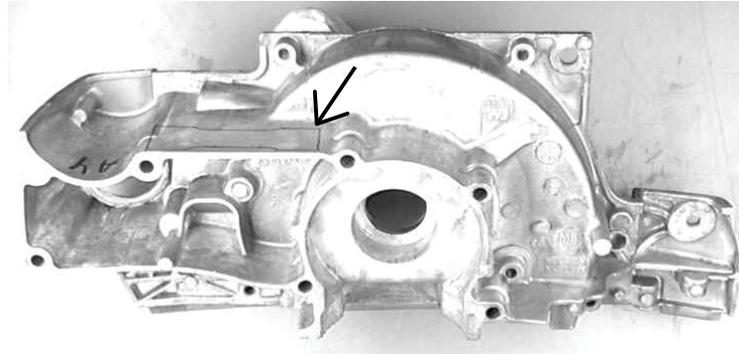


Figure 26: The arrow show where the test bar was taken out from the component.

Table 13: Mechanical properties – result from tension test

	Standard value	100 % ingots					100 % recycled				Standard deviation
		A1	A2	A3	A4	Mean	B1	B2	B3	Mean	
Ultimate strength [MPa]	240	217	223	210	216	216,5	213	209	207	210	4,55
Yield strength [MPa]	130	105	95	87	95	95,5	99	90	90	93	6,59
Strain [%]	3	2,84	2,68	2,04	3,43	2,75	-	1,56	1,62	1,59	0,50

### 2.4.3 Discussion

The summarised conclusion from the analysis is that in-house recycling of biscuits and ingates can be done without any reduction of the quality of the material or deteriorated mechanical properties. The level of oxides will though increase, which can affect the corrosion properties.

#### 2.4.3.1 Material analysis

A round-robin test made within the project showed that there was a difference between the spectrometer results. The difference in the composition of the material can be quite large in casted material, as well as the accuracy of the measuring device. This shows how difficult it could be to make any conclusions based on data from spectrometers. The two methods used in this experiment also shows on this problem.

Regardless of methods and recycling rate the values are within the allowed interval for the standard AZ 91D. The difference between 100 % ingots and 100 % recycled material is very small. The standard values in the table come from EN 1753:1997 and the alloy EN-MC21120, which should best correspond to AZ91.

This means that the recycling rate has no effect on the composition of the material.

Table 14: The material analysis of 100 % ingots respectively recycled.

Standard Hydro	Al	Zn	Mn	Si max	Fe max	Cu max	Ni max	Be	Mg
Ingot AZ 91	8,5-9,5%	0,45-0,9%	0,17-0,40%	0,05%	0,004%	0,025%	0,001%	5-15 ppm	
Component AZ91D	8,3-9,7%	0,35-1,0%	0,15% min	0,1%	0,005%	0,03%	0,002%		

Husqvarna	Al	Zn	Mn	Si	Fe	Cu	Ni	Be	Mg
100 %ingots	9,04	0,706	0,219	0,0371	0,0067	0,008	0,0024	0,0003	
100 % recycled	8,873	0,762	0,228	0,0289	0,008	0,0042	0,0018	0,0003	
Difference	0,1670	-0,0560	-0,0090	0,0082	-0,0013	0,0038	0,0006	0,0000	

KIMAB	Al	Zn	Mn	Si	Fe	Cu	Ni	Be	Mg
100 % ingots	8,5	0,348	0,208		<0,0003	0,0014	0,00018		
100 % recycled	8,27	0,345	0,185		<0,0003	0,0015	0,00018		
Difference	0,2300	0,0030	0,0230	0,0000		-0,0001	0,0000	0,0000	

#### 2.4.3.2 NHIAM –test

The pictures in *Figure 25* show clearly that there are a considerable higher amount of oxides in the melt based on 100 % recycled material.

#### 2.4.3.3 Mechanical properties

Results from the tension test shows no statistically significant difference between the two recycling rates. By using a hypothesis test has this been evaluated. The probability for this to be untrue is 5 %.

It seems though as that the strain value is a little bit lower for the samples made of 100 % recycled material. This could be derived to that a higher level of oxides leads to a less ductile material, because of the more brittle structure.

### 3 SURFACE TREATMENT AND CORROSION PROPERTIES

Magnesium has the lowest corrosion potential of all structural metals. Furthermore, its natural formed oxide does not exhibit good corrosion protection as other metals, especially aluminium. But since it is a technical most interesting metal, with high strength to weight ratio and good casting behaviour, corrosion properties and protection has been thoroughly investigated. Normac has produced a general survey of the corrosion behaviour [8]. The use of magnesium requires either shielding from a corrosive environment by surface treatment or that it is applied in “corrosive benign situations”, e.g. dry interior environments. It is fundamental that galvanic conditions are avoided by proper design. The most eminent general solution is by shielding. Hence, surface treatment and subsequent coating has been evolved throughout the whole period of technical use of magnesium. A survey of current technological level of applied surface treatments has been produced in the framework of Normac [9]. The protection level of established surface treatment methods is also well investigated [10]. However, most information has been gained by accelerated laboratory test methods. Those methods are in many cases well established for certain metals. Implementing them on magnesium may be less successful or even significantly misleading.

This background identifies two topics that was focused upon in this project:

- corrosion behaviour in real exposure of currently evolving coating systems
- relation between accelerated corrosion test methods and real corrosion behaviour by field exposure tests

This chapter concerns the work performed in this project on those two topics. It is introduced by a description of the surface coating systems used in the investigations.

#### 3.1 Surface treatment

The primary reason for surface treatment of magnesium is to increase the corrosion resistance. This is accomplished by a protective surface layer, which may be of different origins or types:

- organic coating, relying on good adhesion by conversion coating or other adhesive pretreatments
- “boasted oxide” by anodising to increase thickness or other mean to increase hardness and stability, often relying on polymer sealing of pores
- metallic coating, mostly used for aesthetic purposes but damage of coating can result in catastrophic galvanic corrosion why metallic coatings may not be recommended for corrosion protection purposes

There is lot of examples and knowledge of commercial and available surface treatments for all of above types mentioned in this [9]. The most economical alternative, by far for any larger scale of production, is organic

coatings. To facilitate good adhesion and ageing properties of organic coats metal substrates are pretreated. Chromating or phosphating is the most used methods. However phosphating is not really applicable to magnesium because large volumes of sludge is produced. Restrictions on chromate contents on vehicles and electronics are to be imposed in the near future. Environmental restrictions on phosphating processes in Sweden may also be imposed due to conservation of the aquatic environment. Hence those two successful types of pretreatments will not be an option in the future. Alternatives are emerging for other metals, as well as for magnesium. This development has been relatively enforced the last 5 years. So in some cases the alternative pretreatments can be considered mature. Some have been applied on magnesium but mostly validated by accelerated test methods.

### 3.1.1 Selection and description of surface treatment processes

Based upon the discussion in previous chapter it was decided to focus the investigation on newly developed chromate free surface conversion treatments and find suitable paint systems. The metal substrate was standardised corrosion plates AM50 supplied by Norsk Hydro, for composition see *Table 2*.

#### 3.1.1.1 *Mechanical cleaning*

All as-cast corrosion plate surfaces were barrel abraded to remove cast skin and other superficial surface defects. This was performed by Finnveden Gjotal AB. For larger products dry-abrasive blast cleaning were performed by either Gjotal or Husqvarna. The abrading processes were performed with normal industrial practice. Hence, no special criteria or measure was imposed.

#### 3.1.1.2 *Conversion coatings*

Two chromate free treatments were compared with a chromate treatment. As a second reference no surface treatment was applied. This was done to investigate any positive primer effect inherent in the paint systems but the main reason was to ensure inferior results in the corrosion tests as “low reference levels”. Below are short descriptions of included surface treatments.

**Gardobond C722:** A conventional yellow chromate treatment performed by Chemetall.

**Oxilan Al 500:** A silane based adhesion promoting treatment performed by Chemetall.

**Alodine160:** A zirconium and permanganate based conversion polymer coating performed by Henkel.

**Untreated surface:** Barrel abraded. This condition was used for all pretreatments above.

### 3.1.1.3 *Paint systems*

Several different paint systems were selected to explore compatibility with the pretreatments, especially the chromate free alternatives.

**Powder coat:** An epoxy/polyester mixed powder, branded Freopox (PB 3003L) supplied by Freilack was applied by Husqvarna. One alternative was to apply an ED primer coat prior to the powder coat. The ED coat was applied by Proton Finishing. This alternative is denoted **ED+Powder**.

**Tikkurila paint system 1:** Water borne paint system with Fontecoat EP primer and Fontedur HB80 as top coat.

**Tikkurila paint system 2:** Solvent based paint system with Temadur primer and Temadur 110 top coat.

**Tikkurila paint system 4:** Solvent based paint system with Temacoat GF primer and Temadur 100 as top coat.

A second water borne system from Tikkurila was planned. But low adhesion after application did not qualify this system for further tests.

## 3.2 **Paint adhesion test**

Paint adhesion test was indirectly performed on all substrates that were exposed to any kind of corrosion test. All test panels were scribed successfully. Poor adhesion was though noted for an intended system from Tikkurila, Fontecryl AP as primer and Fontedur HB 80 as top coat. This paint system was attempted on untreated Mg surface and showed, not surprisingly, inferior adhesion.

## 3.3 **Influences of surface defects on adhesion**

To identify any negative effect on paint adhesion caused by occurring surface defects or irregularities different pretreatments were studied. This should indicate if any pretreatment is more susceptible to a certain kind of surface irregularity.

Substrates with possible surface defects were obtained from the casting process trials with the Bovern, see 2.3, and the recycling tests, see 2.4. The surface defects of the Bovern consists of surface cracks, that are well documented, see 2.3.2. This represents local defects and may result in local loss of adherence. One other type of surface defects that affects the whole surface would be increased amount of elements, as Fe and Cu, or surface inclusions, as oxides, randomly, but closely, distributed on the surface or a general. This may be generated by an increased amount of recycled alloy in the melt. No increase of residual elements, Fe and Cu, was found. But an increase of inclusions has been documented in these trials, see 2.4.2. Components were obtained from this trial as well to represent “general surface defects”.

### 3.3.1 Preparation

Identical test pieces as those subjected to defect identification and mechanical testing was used. The component, the Bovern (AM 50), was cut in two symmetrical halves of which one was used for adhesion tests. All test pieces were abraded as the production standard statues which for the larger component, the Bovern, means it was subjected to blast cleaning. After indication of sites with large and small amount of defects on the Bovern, two locations were cut out. Specific tests were selected to yield a matrix of triplicate objects with varying amounts and types of defects.

The investigation of general surface defects components from Husqvarna were obtained from the recycling trials. The main difference is that no local occurring defects could be expected, rather a general increase of surface inclusions. Hence, the comparison is between components of virgin and recycled melts. Components were obtained with the same conditions as investigated by other means. All test pieces were abraded as the production standard statues, i.e. barrel abraded.

The surfaces were pretreated with Alodine 160, by Henkel, Oxilane Al 500 and Gardobond C722 by Chemetall. Subsequent coating was done with an epoxy/polyester powder coat (Freopox) at Husqvarna. The adhesion test was performed by Scania in both dry condition and after a water soak (40°C for 96 h). The adhesion was tested by three methods, cross hatch, knife cut and jet water on scribe. The tests are well described in appendix 12.

### 3.3.2 Result of paint adhesion effect by surface defects

The paint adhesion test did not yield any indications of adhesion loss. This further means that no distinction could be made between the used surface treatments, substrate alloy and defect type discussed above, i.e. local cracks and possible general increase of surface inclusions.

It is reasonable to imagine that surface defects should affect the surface treatment and subsequently change adhesion properties. At least open surface cracks would have possible detrimental effects since they may act, just as pores, capillary reservoirs for liquids used in the pretreatment process, e.g. acids. But no such detrimental effects have been indicated by the adhesion test performed.

The surface was abraded, as customary, to reduce the “cast skin”. This may obviously reduce the severity of any surface defect. This can well explain why no significant effect on paint adhesion caused by defects was found. But surface abrasion of cast components is an industrial practice and should be included in an evaluation of this kind.

As for surface inclusions any surface defect that may affect the surface treatment may have been abraded. But the increased amount of inclusions in the material does not imply an increase of surface inclusions since the distribution is unknown. Hence, even if this investigation indicates that surface inclusions of the kind generated in this test does not affect the surface treatment it shall not be regarded as confirmed.

Due to the failure of showing the negative effects of surface cracks in this investigation a general observation is that adhesion test after a relative short cycle of humid exposure, 96 h, is not really discriminating for robust systems of thick powder coat. A prolonged time may have proven more discriminating.

## 4 CORROSION

### 4.1 How the surface treatment and paint systems affect the corrosion properties of magnesium alloy AM 50.

Different types of surface treatments and paints have been tested in one year long field exposures, both at Swedish Corrosion Institute's test facilities at Bohus Malmön. They have also been tested in a mobile exposure, where the panels have been exposed under a truck travelling daily between Stockholm and Göteborg (driving distance approximately 150 000 km). Both in the mobile and the marine exposures the test started in the beginning of October 2004. The adhesion of the surface treatment to the substrate has also been tested. The aim with the investigation was to investigate and evaluate the different surface treatments and paints in order to find a suitable alternative to Chromate, that is currently used as surface treatment for magnesium alloys.

#### 4.1.1 Experimental

##### 4.1.1.1 *Marine Field exposure*

In all of the experiments magnesium alloy AM50 have been used, delivered by Norsk Hydro. The size of the panels has been 100x140x3 mm. In all of the panels two scribes with a width of 1 mm have been made, using a pneumatic scribing tool, see *Figure 27*.

Before exposure one fastener of stainless steel was mounted in contact with the lower of the two scribes. Both the front side and the rear side of the panels have been surface treated and painted but only the front side has been evaluated regarding the corrosion resistance.

In the marine exposure at Bohus Malmön a number of different surface treatments and paint systems have been exposed for one year, with the start in October.



Figure 27: Panels exposed at the marine field station at Bohus Malmön. All of the panels have two scribes, a stainless steel fastener have been mounted in the lower of the two scribes.

The different combinations that have been tested are given in **Table 15**.

Table 15: Surface treatments and paint systems on panels exposed at Bohus Malmön. In total 48 panels.

Surface treatment		Paint system					Total
		ED + powder coat	Powder coat	Water borne paint	Solvent borne paint	Without paint	
<b>Alodine 160</b>	<b>(Ti/Zr)</b>	3	3	3	3	-	12
<b>Oxsilan Al 0500</b>	<b>(Silane)</b>	3	3	3	3	-	12
<b>Gardobond C722</b>	<b>(Chromated)</b>	3	3	3	3	-	12
<b>Without surface treatment</b>		-	-	3	6	3	12
<b>Total</b>		<b>9</b>	<b>9</b>	<b>12</b>	<b>15</b>	<b>3</b>	<b>48</b>

#### 4.1.1.2 Mobile exposure

In the mobile exposure a smaller matrix have been used with three different surface treatments and two different paint systems (**Table 16**). Of each surface treatment three replicas have been exposed. This gives a total of 15 panels that have been exposed in the mobile exposure. In both of the exposure untreated panels have been exposed in order to compare the overall atmospheric corrosion of magnesium alloy AM50.

Table 16: Surface treatments and paint systems on panels exposed in the mobile exposure and the accelerated tests.

Surface treatment		Powder coat	Water borne paint	Without paint	Total		
<b>Alodine 160 (Ti/Zr)</b>	<b>3</b>	-	-	<b>3</b>			
<b>Oxsilan Al 0500 (Silane)</b>	<b>3</b>	-	-	<b>3</b>			
<b>Gardobond C722 (Chromated)</b>	<b>3</b>	-	-	<b>3</b>			
<b>Without surface treatment</b>	-	<b>3</b>	<b>3</b>	<b>6</b>			
<b>Total</b>	<b>9</b>	<b>3</b>	<b>3</b>	<b>15</b>			

#### 4.1.1.3 Evaluation methods

Before the evaluation of the panels the stainless steel fastener has been removed and the panels cleaned. The corrosion attack has been evaluated measuring the maximum corrosion attack, measured from the scribe (see Figure 28).

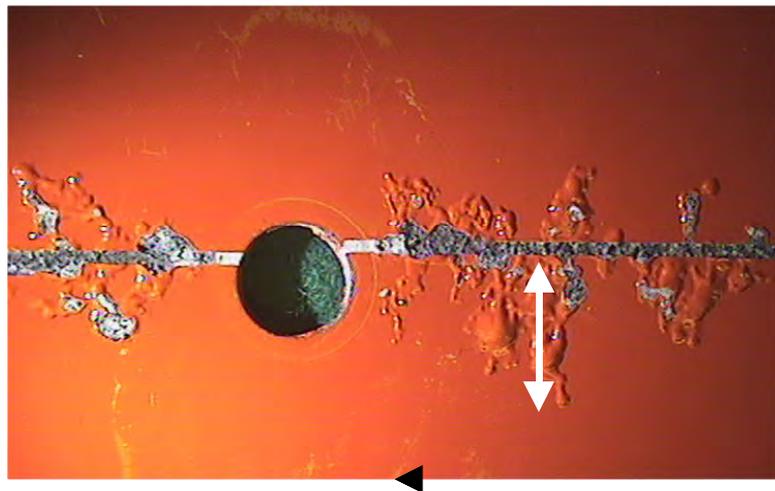


Figure 28: The corrosion attack has been evaluated measuring the maximum corrosion attack, measured from the scribe, in the figure marked with a white arrow.

#### 4.1.1.4 Adhesion

The adhesion of the paint systems have been tested using both pull-off test, according to ISO-4624:2002 standard and cross-cut test according to Volvo standard VCS 1029,5472.

In the pull-off test two test cylinders, each with an area of  $3.14 \text{ cm}^2$ , was glued onto the unexposed coated Mg alloy surface, using two different types of glue, a two component epoxy and a cyanoacrylate based glue. The adhesion has been tested using a precision adhesion tester. After the test cylinder had detached from the surface of the sample, both the surface of

the test cylinder and the surface of the substrate were examined. The examination of the surfaces revealed where, in which coating layer, the failure had occurred.

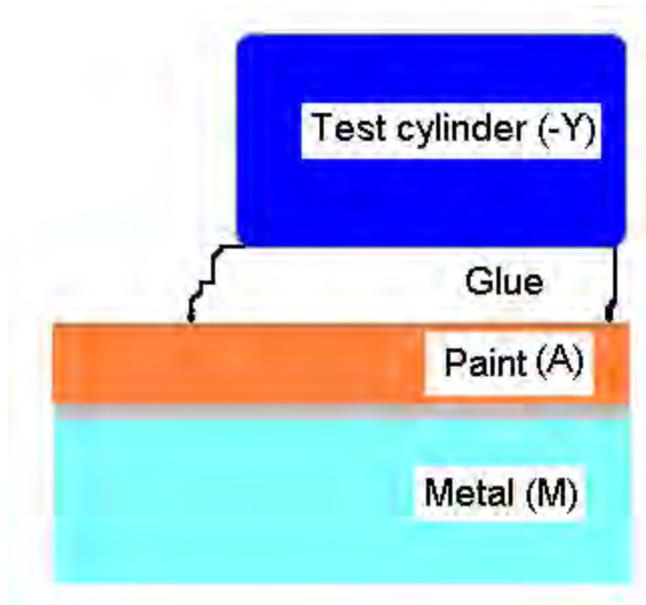


Figure 29: Schematic image over the adhesion test setup. The test cylinder is glued onto the coated magnesium surface.

In the cross-cut test a 1 mm cutting tool has been used. The tool has been scratched over the surface of the unexposed panels forming a net pattern. Loose paint from the surface have been removed with a brush and tape, the pattern have been evaluated using standard STD 1029,5472. The panels have then been exposed to humid air for 24h according to standard VCS 1027,33759, and the panels have been cut with the cross-cut tool and have then again been evaluated. The samples from Bohus Malmön have also been tested using the cross-cut test.

#### 4.1.2 Results from field exposures

##### 4.1.2.1 Marine field exposure

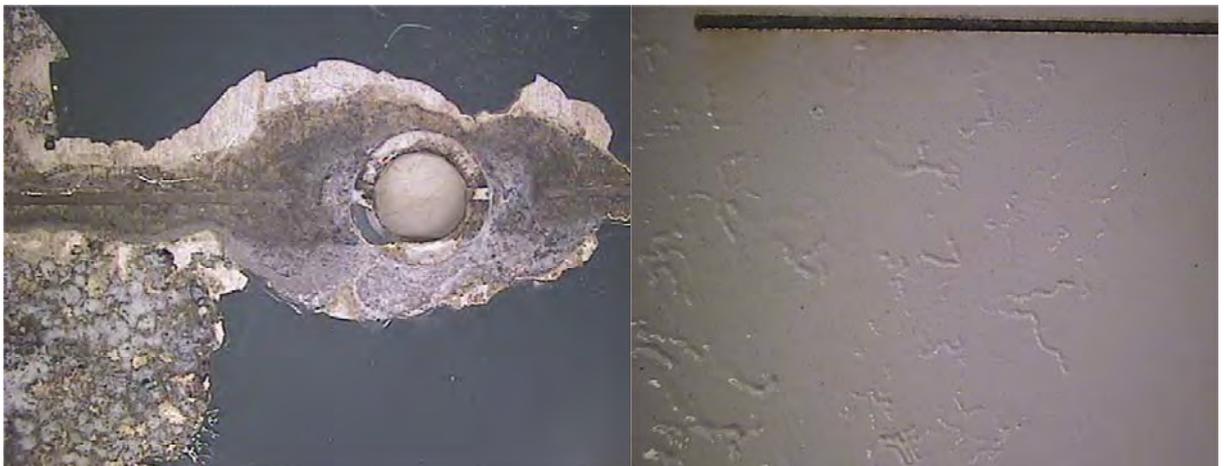
In the marine exposure uncoated panels have been exposed to get a rough idea about the general corrosion of magnesium alloy AM50. In *Table 17* the corrosion rate of magnesium alloy is compared to different bare metal panels exposed at Bohus Malmön. The evaluation of the corrosion values for 2005 for bare metals is not yet finished, therefore the corrosion values for magnesium alloy AM50 is compared to corrosion values for the bare metals obtained under 2004.

*Table 17: The corrosion rate of magnesium AM50 exposed under 2005 compared with bare metals exposed at Bohus Malmö under 2004. Corrosion rate is given in  $g/m^2$ , year.*

	<b>Carbon Steel</b>	<b>Zink</b>	<b>Copper</b>	<b>Aluminium</b>	<b>Magnesium AM50</b>
Bohus Malmö, Kvarnwik	597 ± 91	6,6 ± 0,3	23,8 ± 2,0	1,5 ± 0,6	77,0 ± 7,8

The high corrosion rate seen for the magnesium alloy is dependent on the high  $Cl^-$  concentration at the exposure site. The  $Cl^-$  concentration has a high influence on the corrosion rate of magnesium [11]. In the marine exposure a number of different surface treatments and paints have been tested (*Table 15*). After a visual examination of the exposed panels it's clear that the panels without surface treatment have withstood the marine environment poorly. As can be seen in *Figure 30* the paint layer has detached in big flakes on the panels painted with Tik-sys 1, this was also valid for the panels treated with Tik-sys 2. As can be seen in the figure the corrosion attacks have occurred under the paint layer, thereby undermined the paint layer.

Tik-sys 4, right in *Figure 30*, behaved better than Tik-sys 1 and 2 regarding the corrosion behaviour. However as can be seen a big part of the Tik-sys 4 surface was covered with filiform corrosion. The filiform corrosion seems to start from different point on the surface and not in the immediate vicinity of the scribe, indicating that the paint has pores where the filiform attack started. The poor behaviour of the samples without pretreatment can also be seen in *Figure 31* and *Figure 32* where the average of the maximum corrosion attacks measured scribes is shown.



*Figure 30: Left: Bi-metallic scribe of Tik-sys 1, without surface treatment. Right: upper Scribe of Tik-sys 4.*

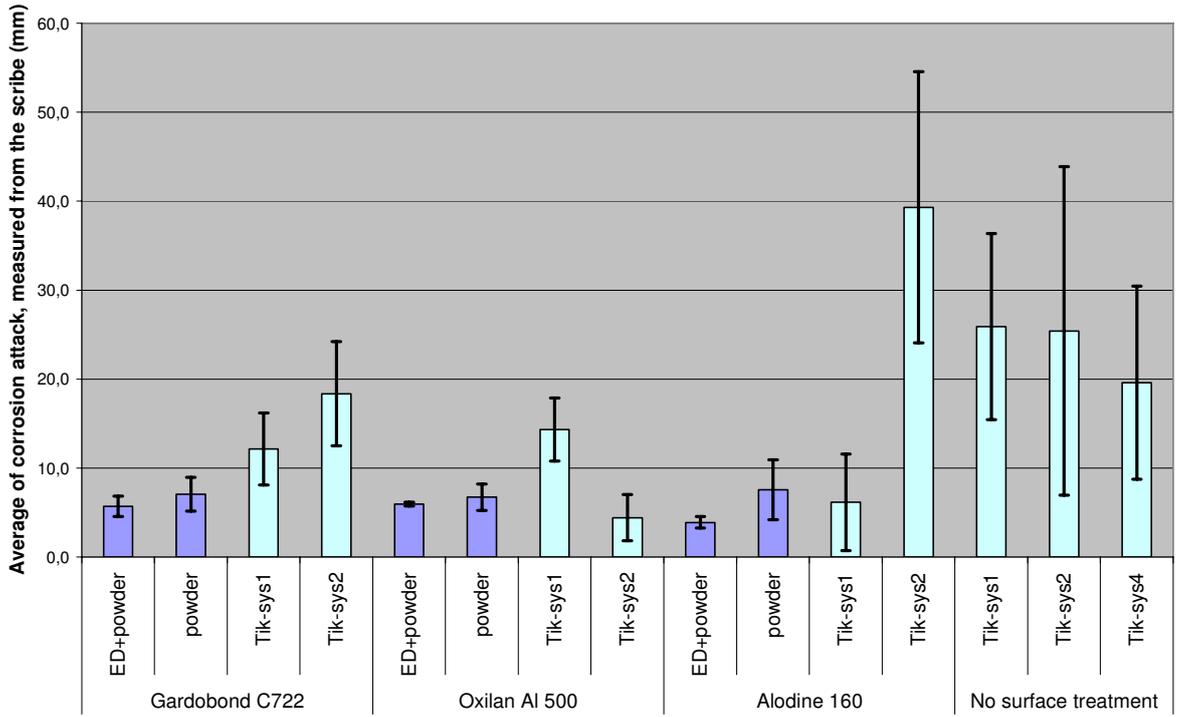


Figure 31: Average of the corrosion attack measured from the lower scribe with fastener. The lighter colour indicates filiform corrosion attack.

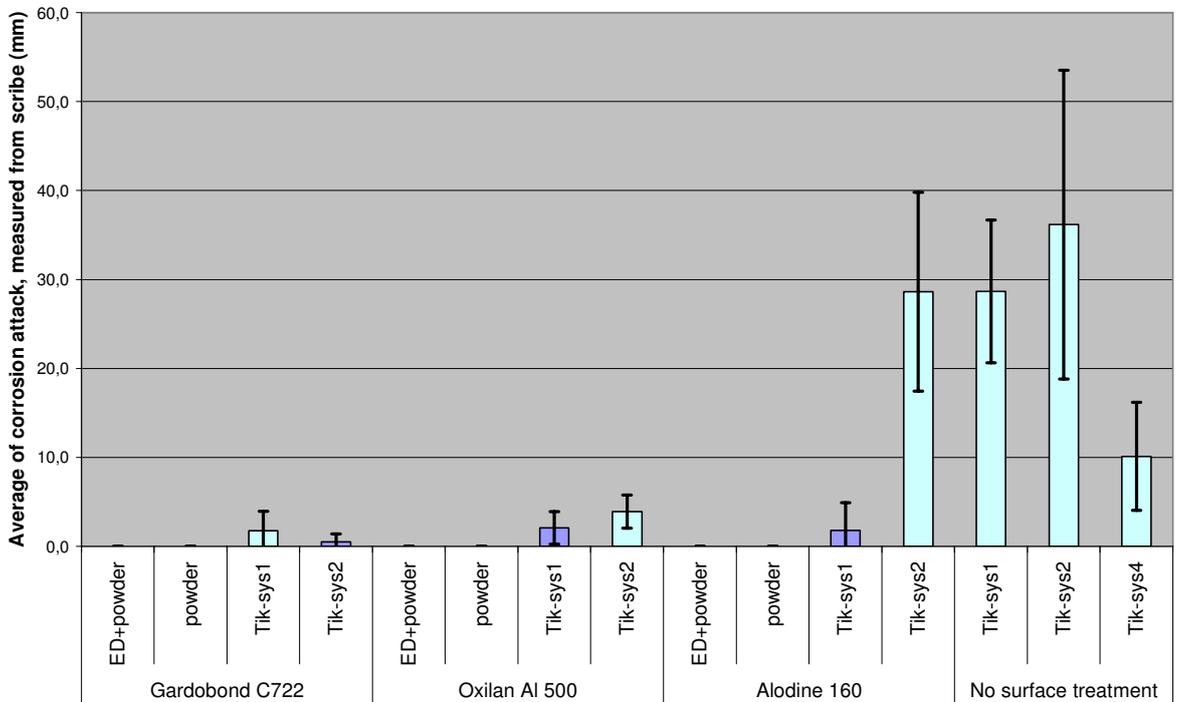


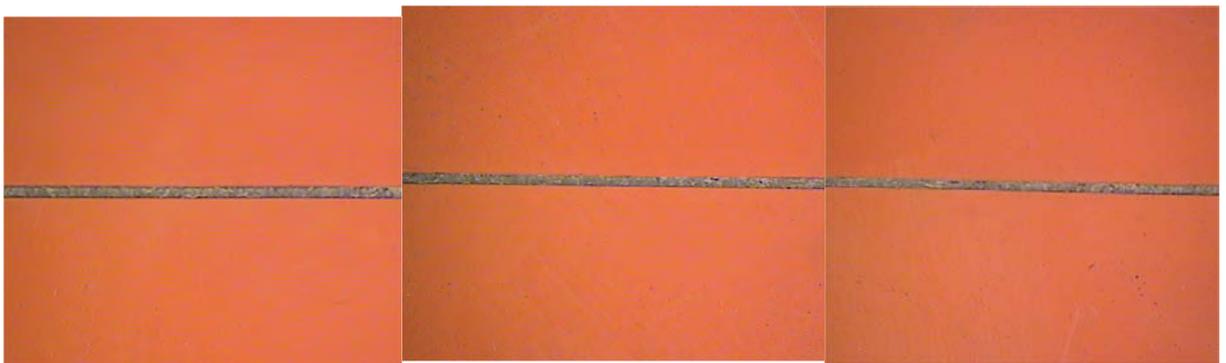
Figure 32: Average of the corrosion attack measured from the upper scribe, without fastener. The lighter colour indicates filiform corrosion attack.

The panels treated with powder paint shows good results. In *Figure 32* and *Figure 33* it can be seen that on the panels treated with powder coat the upper scribe is unaffected after one years exposure at Bohus Malmö. The lower scribe is only affected around the fastener and not around the rest of the scribe, this is expected since the contact between the coated magnesium panel and the stainless steel fastener gives a very high driving force for bi-metallic corrosion.

It can also be seen in *Figure 31* - *Figure 34* that there is no apparent difference between different pretreatments, coated with powder coat. The alternative pretreatments Oxilan Al 500 and Alodine 160 behave in a similar way as the chrome based Gardobond C722 pretreatment. The good performance of the powder coated can be explained by the better adhesion of the paint.

From *Figure 31* and *Figure 32* it can also be seen that the paint is of crucial importance. The powder coat shows very good corrosion resistance but the water borne Tik-sys 1 and the solvent borne Tik-sys 2 shows less good results.

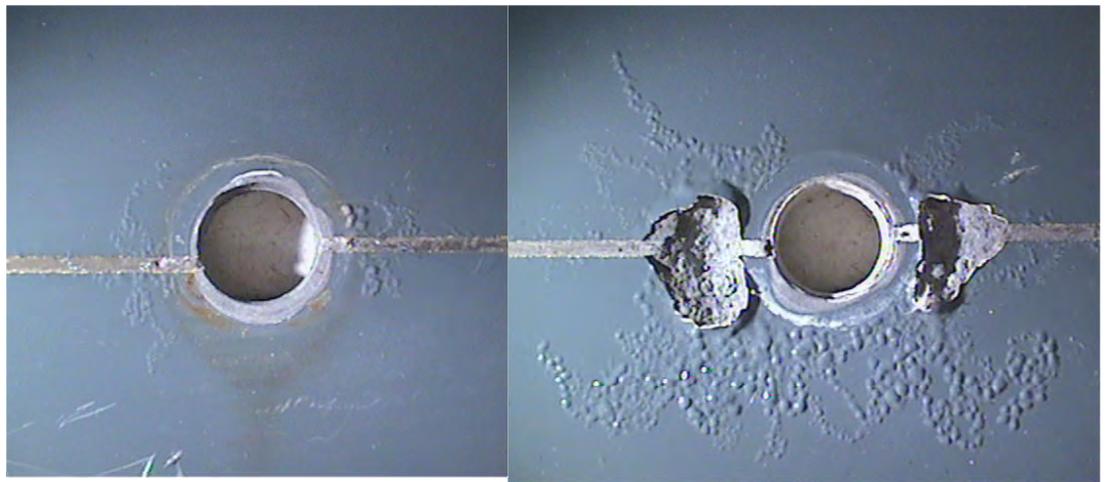
In the case of samples treated with Tik-sys 1 or 2 the corrosion is mostly in the form of filiform corrosion, as indicated by the lighter blue colour in the columns in *Figure 31*. For example Alodine 160 coated with Tik-sys 2, in this system the filiform corrosion is severe. It should also be noted that the deviation in delamination is bigger between the samples treated with Tik-sys 1 and Tik-sys 2. Some of the panels show good results, but other panels treated in the same way is heavily affected by filiform corrosion (*Figure 35*). This is probably due to the fact that some specimens have poor contact between the fastener and the magnesium plate. The samples treated with Tik-sys 1 and Tik-sys 2 the corrosion attack from the bimetallic coupling on the lower scribe is not that severe, the problem is instead the filiform corrosion.



*Figure 33: Upper scribe of panels pretreated with: Gardobond C722 (left), Oxilan Al 500 (middle) Alodine160 (right). All of the panels are painted with powder coat. The panels have been exposed at Bohus Malmö for one year.*

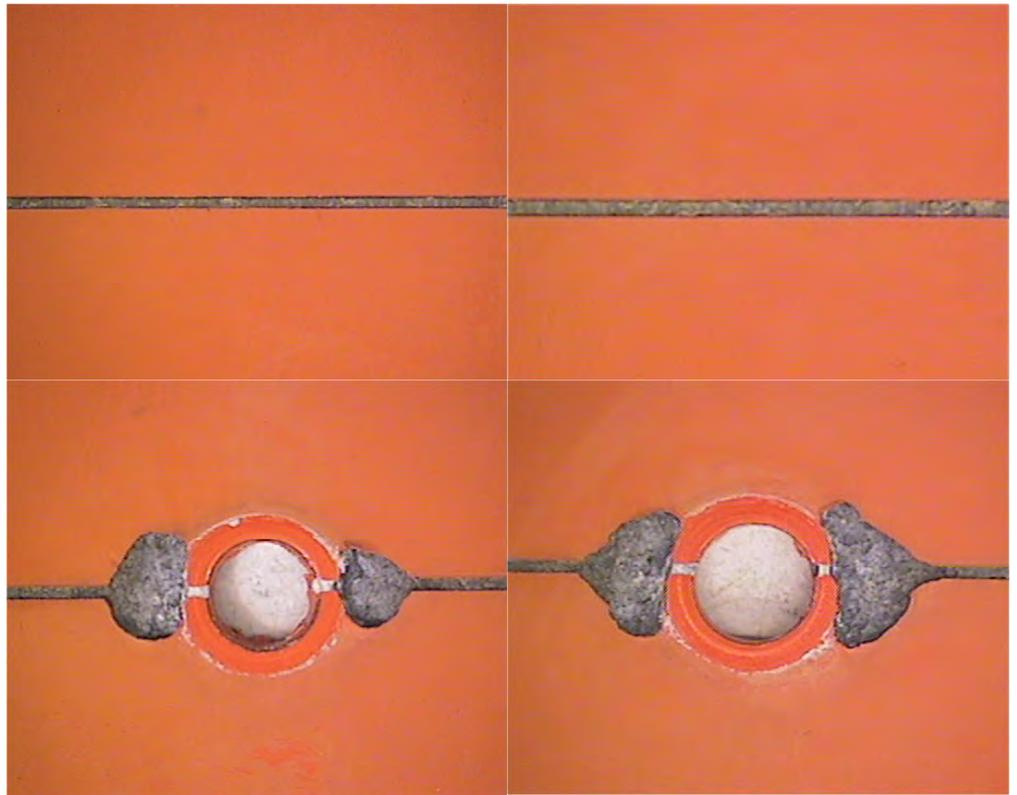


*Figure 34: Bottom scribe with bi-metallic coupling removed of panels pretreated with: Gardobond C722 (left), Oxilan Al 500 (middle) and Alodine 160 (right). All of the panels are painted with powder coat. The panels have been exposed at Bohus Malmön for one year.*



*Figure 35: Panels treated with Gardobond C722 and Tik-sys.*

In *Figure 36* the left panel have been pretreated with Gardobond C722 and powder coat, the right panel has been treated with Gardobond C722, ED and powder coat. As can be seen there is no apparent difference between the two, this can also be viewed in the diagrams in *Figure 31* and *Figure 32*, The powder coat has as good adhesion towards the metal surface as the ED-primer and the coating systems approximately the same corrosion resistance.



*Figure 36: Scribes with and without the bi-metallic coupling on panels pretreated with: Gardobond C722 and powder coat (left) and Gardobond C722, ED and powder coat (right).*

#### 4.1.2.2 *Mobile field exposure results*

The corrosion attacks on the panels exposed in the mobile exposure looks similar compared to the corrosion attack on the panels in the marine exposure (compare *Figure 37* with *Figure 33* and *Figure 34*). No corrosion could be seen around the upper scribe of the samples protected with powder coat. In connection with the scribe with metallic coupling there is deep pits around the removed fastener, however the rest of the scribe is unaffected by corrosion and paint release.

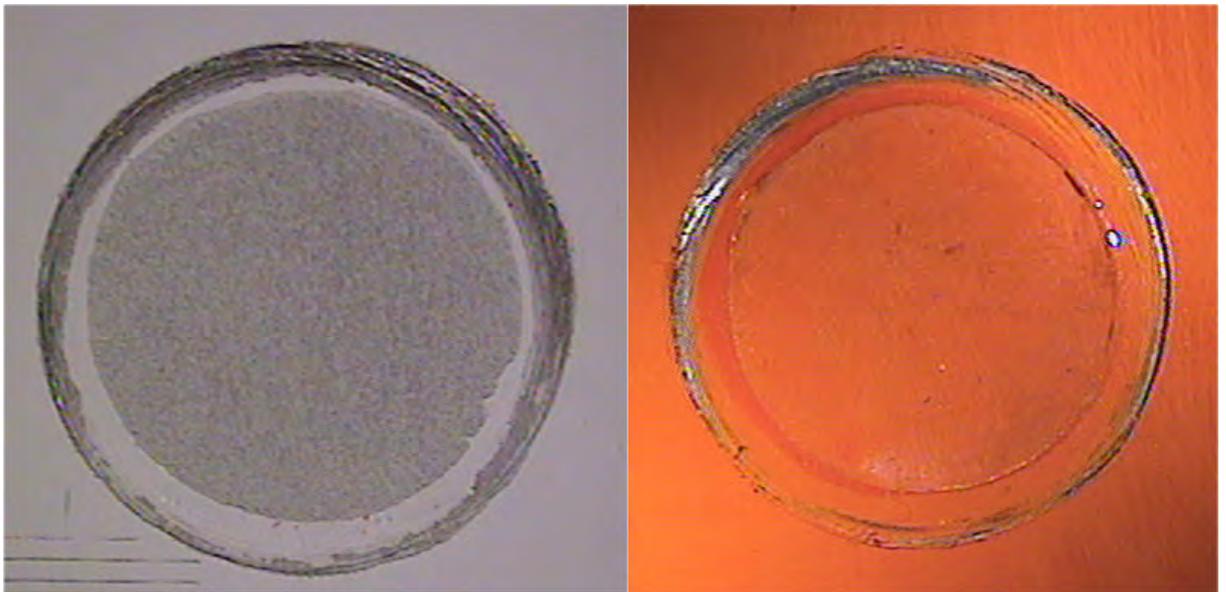
The panels without surface treatment have withstood the test poorly, with heavy blister formation under the paint. Also in the mobile exposure it can be said that the alternative pretreatments Alodin 160 and Oxilan Al 500 is as good as the chrome containing Gardobond C722.



*Figure 37: Panels exposed in the mobile exposure for one year, from the left panels pretreated with Gardobond C722, Oxilan Al 500, Alodine 160 and no pretreatment.*

#### 4.1.2.3 Adhesion

Adhesion tests of both unexposed and exposed panels have been performed. Unexposed panels have been used in the pull-off test where the adhesion have been tested by using an adhesion tester. The results are shown in *Figure 39*.



*Figure 38: Unexposed panels after the pull-off test. Left: Alodine160 with Tik-sys 1, The break has occurred in the paint layer Right: Alodine 160 with powder coat. 100% of the break have occurred between the test cylinder and the glue.*

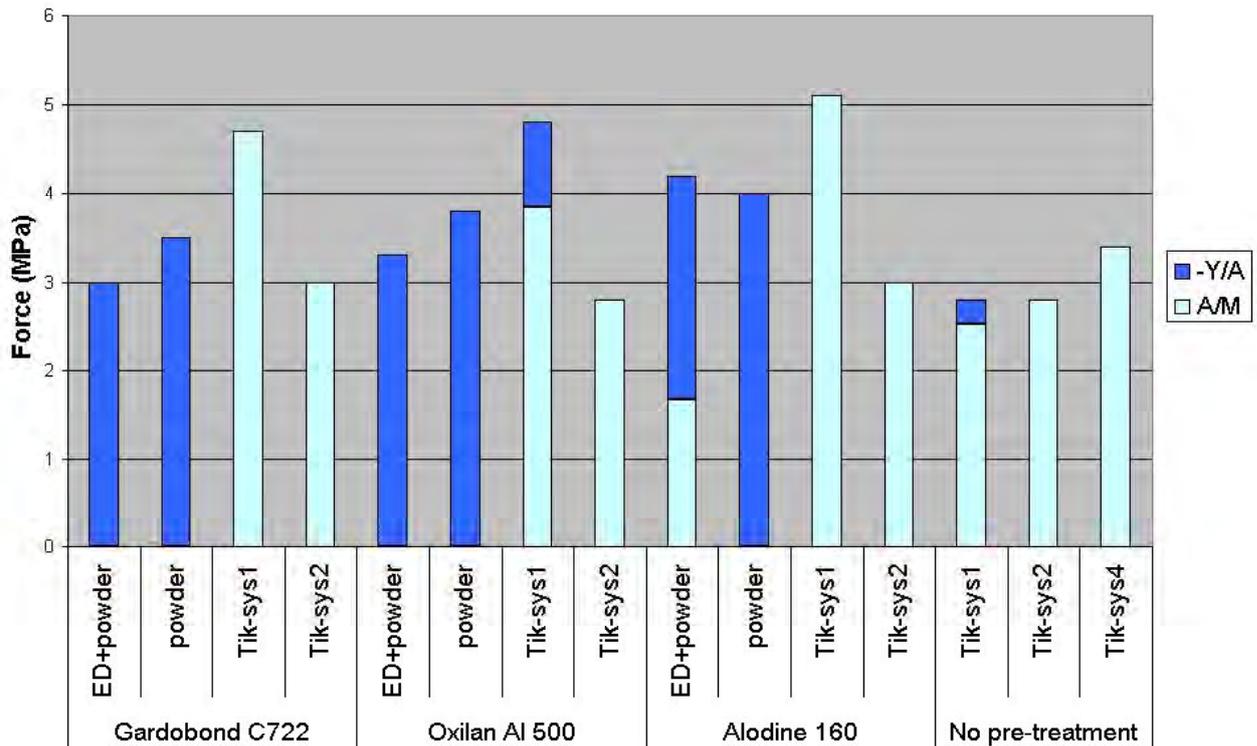


Figure 39: Adhesion of unexposed panels measured by pull-off test.

On the X-axis in Figure 39 the different kind of pre-treatment and paint systems is displayed. The detachment of the test cylinder is due to failure between one or more of the coating layers. The failure can occur either between the test cylinder and the paint (-Y/A), or between the paint and the metall surface (A/M) (see Figure 29 and Figure 38). By examining the surfaces on both the substrate and the test cylinder an examination of where the failure has occurred could be made. (Often the failure was not exclusively due to a clean break between two layers but partially due to break between two layers and partially between two other layers.) Where the failure has occurred is given as a percentage of the maximum force.

The examination shows that on the powder coated panels the break is mainly caused due to a fracture between the test cylinder and the paint layer, i.e. the glue layer is the first layer to break. This means that the adhesion is at least the minimum value given in Figure 39. No apparent difference can be seen between the different surface treatment Alodin 160, Gardobond C722 and Oxilan Al 500 protected with powder coat. Also no difference could be seen between the panels treated with ED and powder coat and the panels treated with only the powder coat. On the panels treated with the water or solvent borne paint, the failure has mainly occurred between the pretreatment and the paint layer.

The adhesion of the paint has also been tested using a cross-cut 1mm cutting tool. The cross-cut test has been preformed on unexposed panels, the panels have then been exposed to humid air in climate chamber for 24 h and the panels have then again been evaluated. Panels exposed at Bohus Malmön have also been evaluated using the cross-cut test. The result from the cross cut test have been evaluated using standard STD VOLVO VCS 1029,5472 were the cuts is classified using following grades:

- 0 = No remarks  
 1 = Somewhat uneven cuts.  
 2 = Clearly uneven cuts  
 3 = Very uneven cuts  
 4 = Severe flaking of material.  
 5 = Very severe flaking

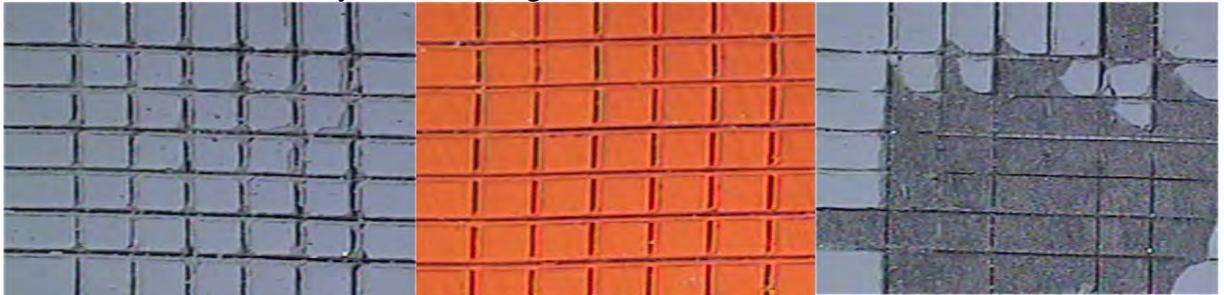


Figure 40: Unexposed panels after cross-cut test, Right: Gardobond C722 with Tik-sys 2, Middle: Alodine 160 with powder coat, Left: Panels without surface treatment coated with Tik-sys 2.

Table 18: The results from the cross-cut test. Unexposed panels, panels exposed to humid air in climate chamber for 24 h and panels exposed at Bohus Malmön have been evaluated using the cross-cut test.

		Unexposed	After exposure 24h 100% RH	Exposed 1y Bohus Malmön
Gardobond C722	ED+powder	0	0	0
Gardobond C722	powder	0	0	0
Gardobond C722	Tik-sys1	0	0	0
Gardobond C722	Tik-sys2	1	1	1
Oxilan Al 500	ED+powder	0	0	0
Oxilan Al 500	powder	0	0	0
Oxilan Al 500	Tik-sys1	0	0	0
Oxilan Al 500	Tik-sys2	1	1	1
Alodine 160	ED+powder	0	0	0
Alodine 160	powder	0	0	0
Alodine 160	Tik-sys1	1	1	0
Alodine 160	Tik-sys2	2	2	3
No pretreatment	Tik-sys1	0	2	1
No pretreatment	Tik-sys2	5	5	3
No pretreatment	Tik-sys4	5	2	3

As can be seen in both *Figure 40* and *Table 18*, the panels without surface treatment have a poor adhesion. Panels treated with powder coat manage the cross-cut test well. Tik-sys 2 have a lower adhesion in the cross-cut test,

this is valid for both the Alodine160, Oxilan Al 500 and Gardobond C722 pretreatment. Worth to notice is that exposure to humid air for 24h or 1 years marine exposure does not affect the adhesion of the paint in a larger extent.

## 4.2 Comparison between different accelerated corrosion test.

Surface treated panels of AM50 have been tested and compared in four different accelerated corrosion tests. The results from the accelerated tests have then been compared with the mobile and marine exposures. The aim with the tests has been to study the correlation between the accelerated test and the marine and mobile exposures. A smaller matrix has been used in the accelerated tests, compared to the marine exposure at Bohus Malmö, the matrix can be seen in *Table 16*. As-cast specimens have also been exposed in the accelerated tests as well as the field exposures and are compared in *Figure 45*.

### 4.2.1 Experimental: Accelerated corrosion tests

Four different accelerated corrosion tests have been conducted: GM- 9540P test conducted by Norsk Hydro, Mud-VICT conducted by Volvo, SCAB conducted by Swedish Corrosion Institute and VDA conducted by Scania. In the accelerated tests three different surface treatments in combination with powder coat have been tested together with panels without surface pretreatment. For each of the different surface treatments there have been three replicates. The experimental set-up for the different accelerated corrosion tests is shortly explained below.

#### 4.2.1.1 *GM test*

GM- 9540P test has been conducted by Norsk Hydro. In the GM test the temperature and relative humidity is cycled in three 8h cycles according to *Figure 41*. In the first of the three cycles salt mist is introduced, second cycle consists of high humidity and high temperature, last cycle is a 8h dry up period. The duration of the test is 40 days.

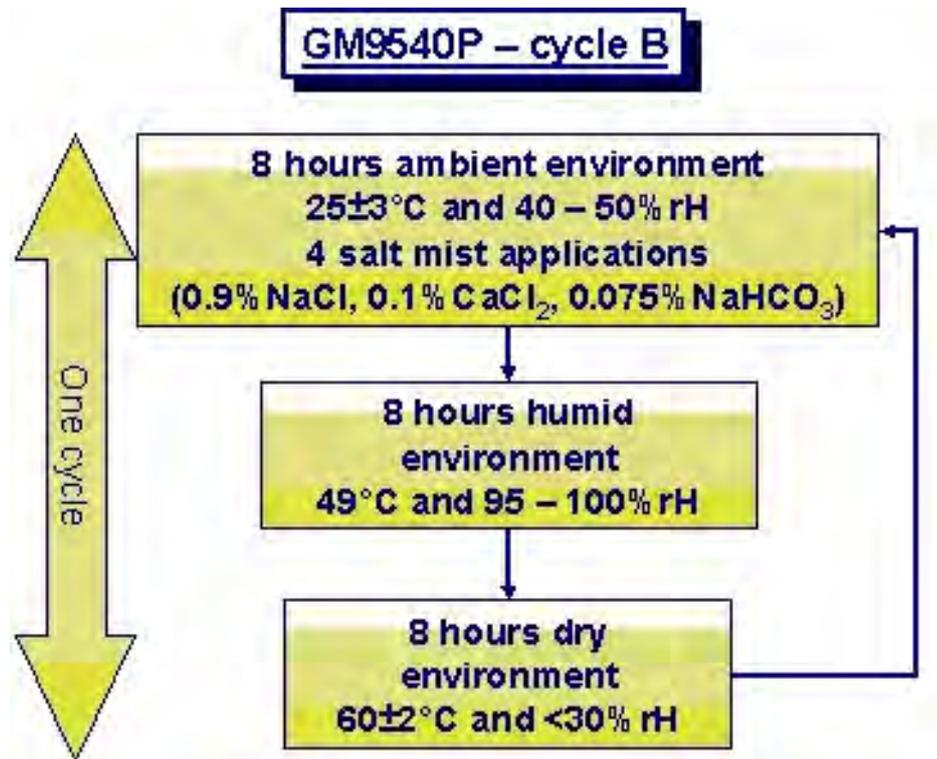


Figure 41 : GM- 9540P test conducted by Norsk Hydro, duration 40 days.

#### 4.2.1.2 SCAB

In the SCAB test the panels were mounted on racks located on the balcony of Swedish Corrosion Institutes facilities in Stockholm and exposed to an outdoor SCAB-testing according to SS-ISO 11 474. According to the standard the specimens are exposed with 45° inclination towards south and sprayed twice a week with a 3% sodium chloride solution. The exposure period was three months.



Figure 42: Panels exposed in SCAB test, at the Swedish Corrosion Institute. Duration of the test was 3 months.

### 4.2.1.3 Mud VICT test

Mud VICT has been conducted by Volvo according to standard VCS 1027,149. In the MUD-VICT artificial road mud is applied on the panels, instead of the salt spray periods. The artificial road mud consistent of 1% NaCl, 11% kaolin, 88% sand 40 ml deionised water, for 100 g solution. The panels are then exposed in a VICT test. The VICT test starts with 4 h in high relative humidity this is followed by a dry up period of 4h with lower relative humidity and higher temperature (see *Figure 43*). The duration of the test was 6 weeks.

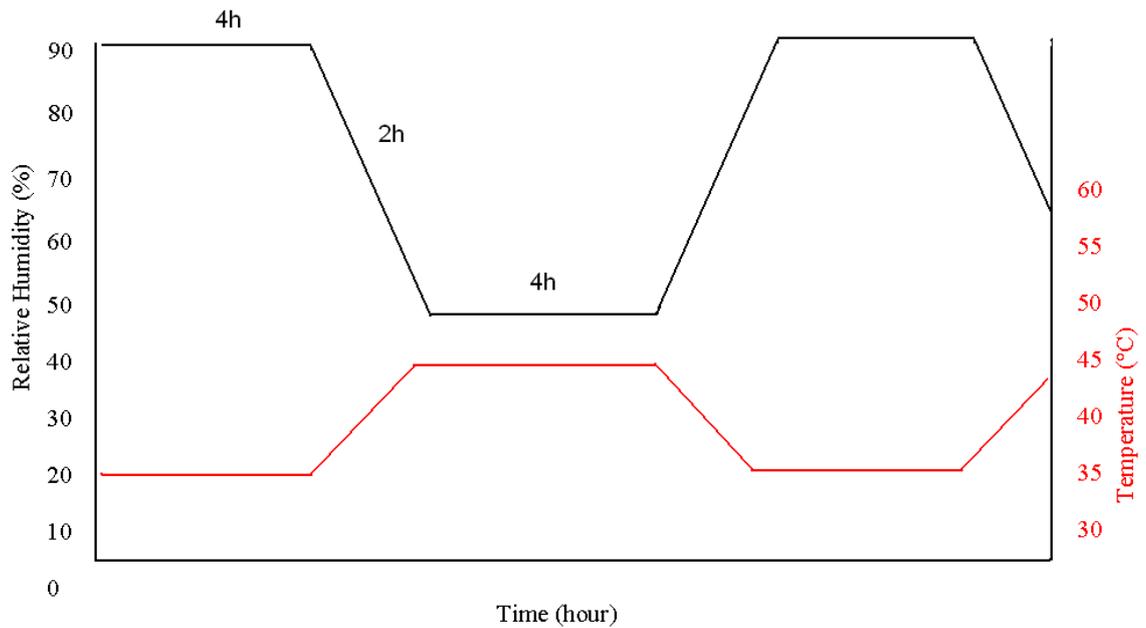


Figure 43: Schematic diagram over the VICT test. Duration 6 weeks.

### 4.2.1.4 VDA 621-415

Scania has conducted the VDA 621-415 test. A cycle in the VDA test has a duration of one week. The cycle starts with one day of 5% NaCl mist, followed by four days with cycled high and low relative humidity according to *Figure 44*, day six and seven in the cycle is a dry-up period. After seven days the cycle starts over. The test duration is 10 weeks.

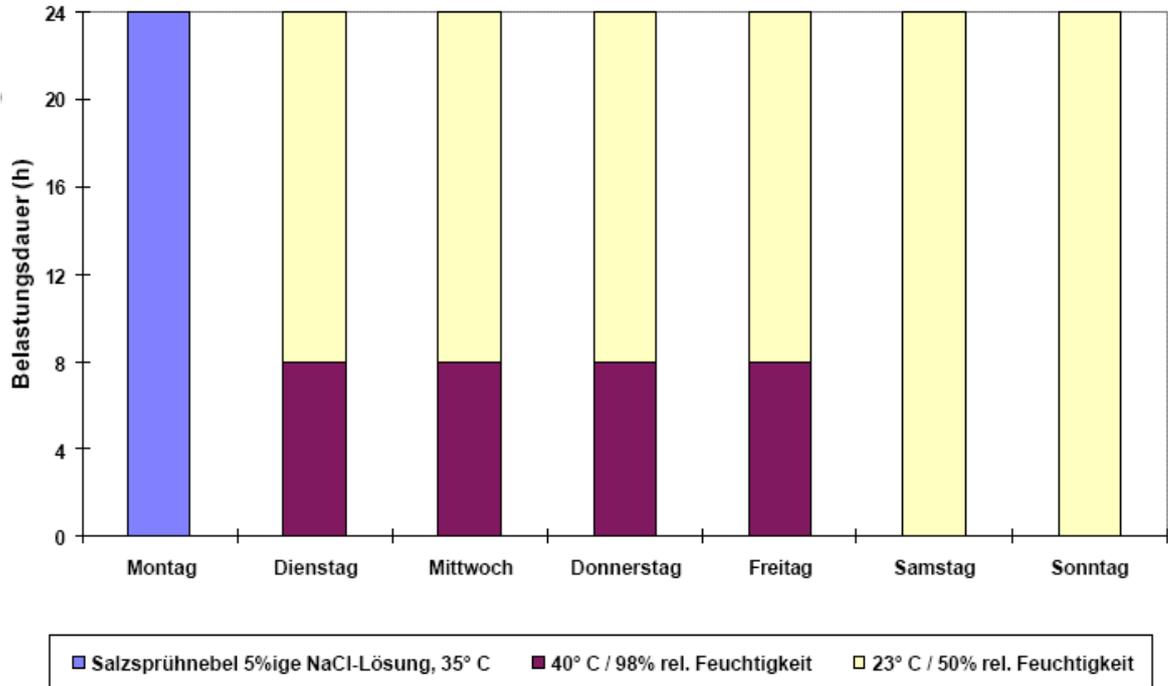


Figure 44: VDA 621-415 test. Duration is 10 weeks.

#### 4.2.2 Results: Accelerated corrosion tests

The mass loss of uncoated AM50 panels exposed in the different accelerated tests can be seen in *Figure 45*. The mass loss for the marine and the mobile exposures can also be seen in the same figure. The corrosion in *Figure 45* is given in  $\text{g/m}^2$ , i.e. corrosion versus time is not given, since it's interesting to see the accelerating factor of each test. The highest mass loss can be seen for the VDA test. Worth to notice is the high scattering between the three panels for the VDA test. The corrosion rate of the marine and the mobile exposures is more or less the same. The corrosion in the GM and SCAB tests is lower compare to the two field tests. It can also be seen that the standard deviation of the GM, SCAB and Mud -VICT is comparable to the field exposure. In *Figure 46* and *Figure 47* the average of the corrosion attacks measured from the scribe is shown, for the different accelerated tests as well as the field exposures.

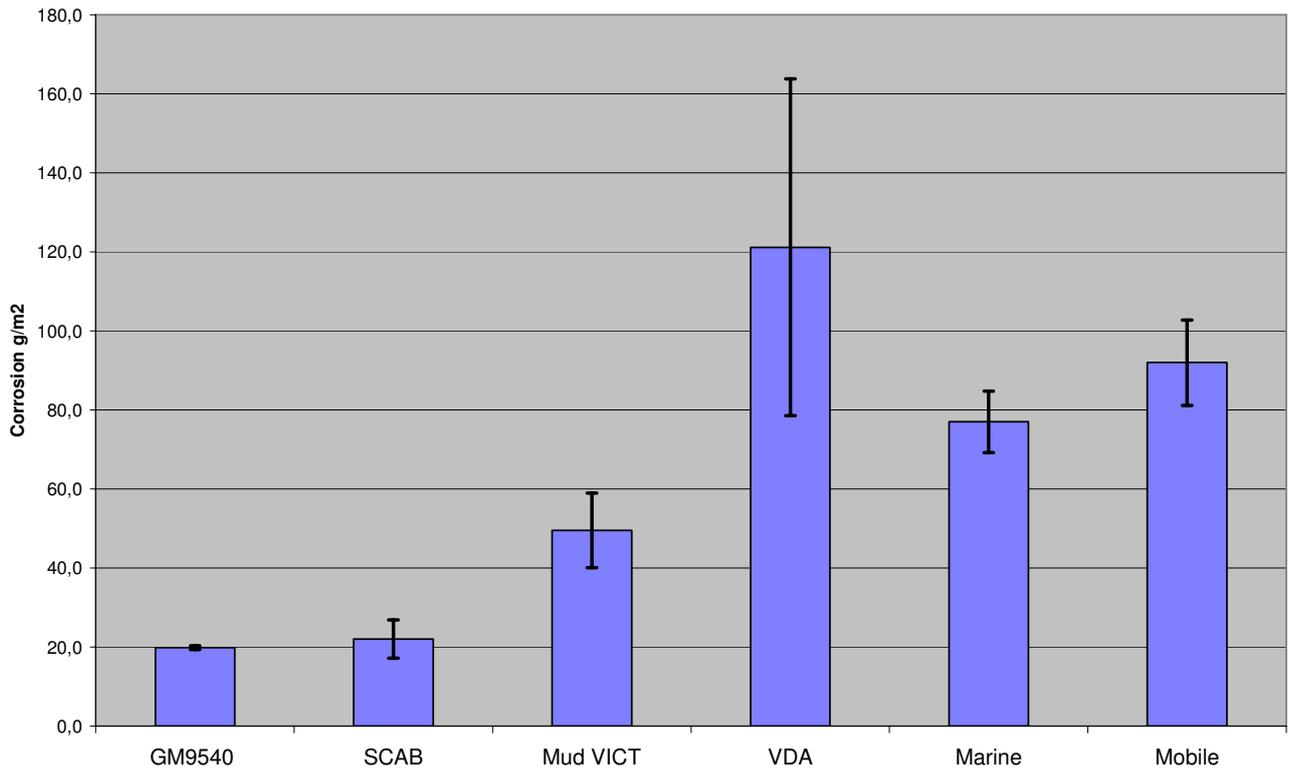


Figure 45: Corrosion of As-cast AM50 panels exposed in different accelerated tests and in marine and mobile exposures. Black bars represent the standard deviation out of three replicas.

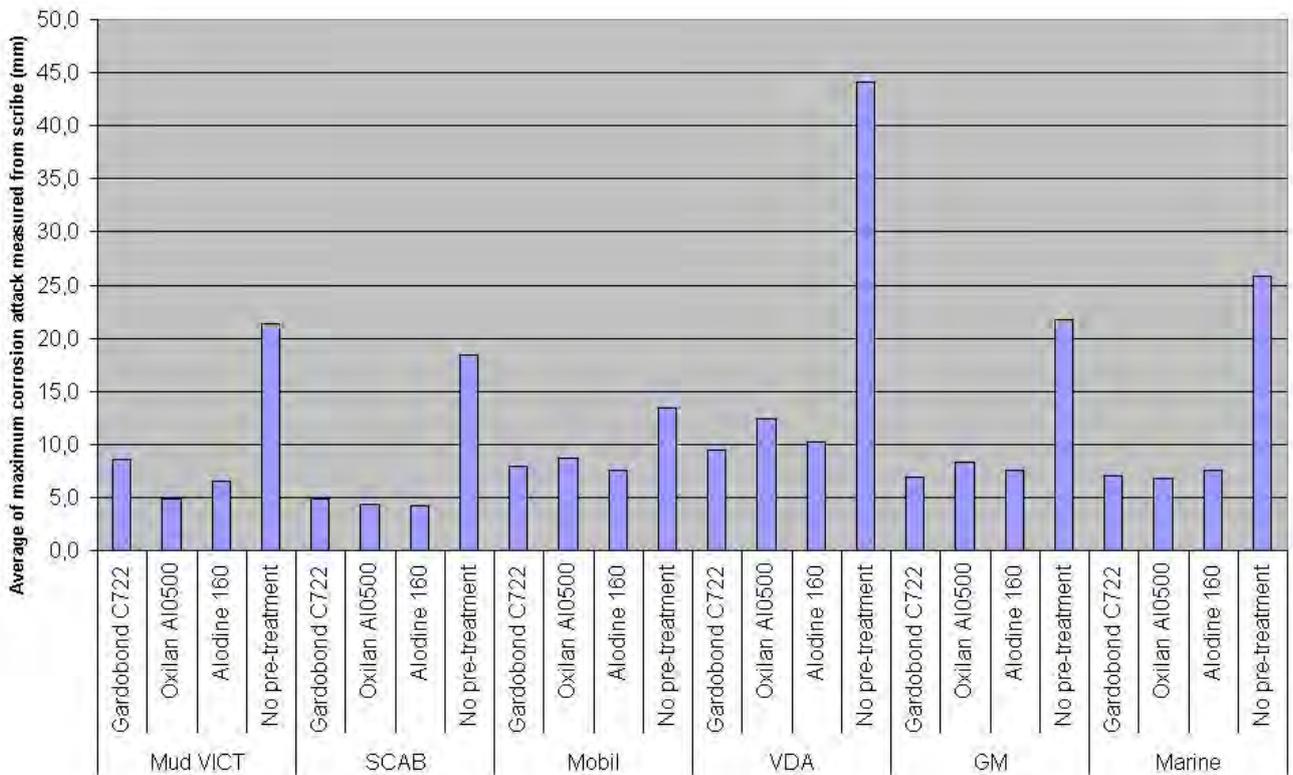


Figure 46: Average of the corrosion attack measured from the lower scribe with fastener for the different accelerated tests as well as the field exposures.

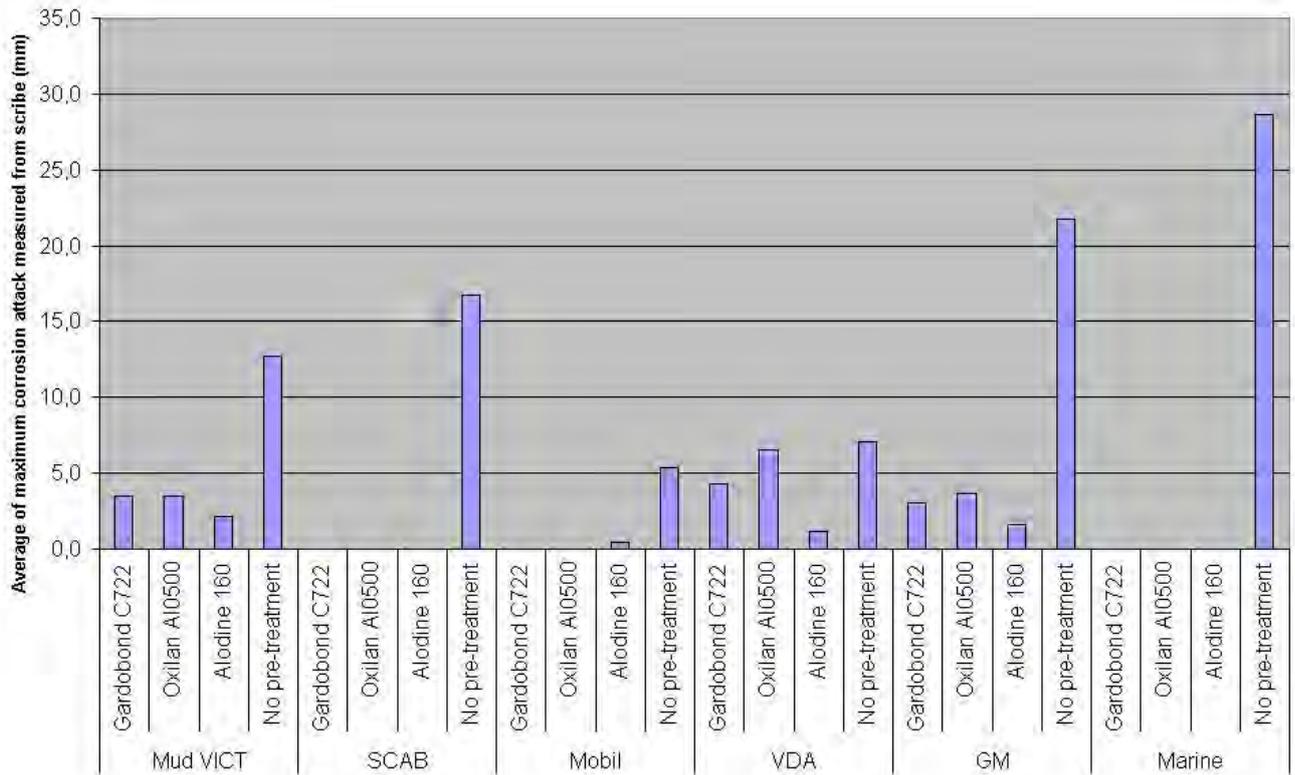


Figure 47: Average of the corrosion attack measured from the upper scribe for the different accelerated tests as well as the field exposures.

Table 19 gives the acceleration factor of the different accelerated tests. The acceleration factor is defined according to the following equation:

$$Acc.Factor = \frac{Corr.Rate(acc.test)}{Corr.Rate(field)} \times const. \quad [1]$$

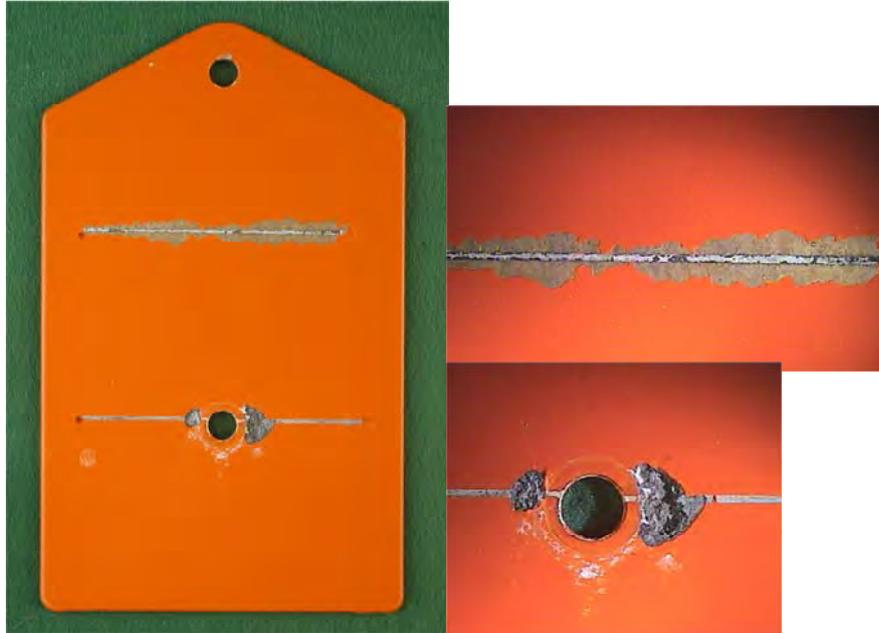
The constant is the ratio of exposure period in the marine exposure and the accelerated corrosion test.

Table 19: Acceleration factor of the different accelerated tests.

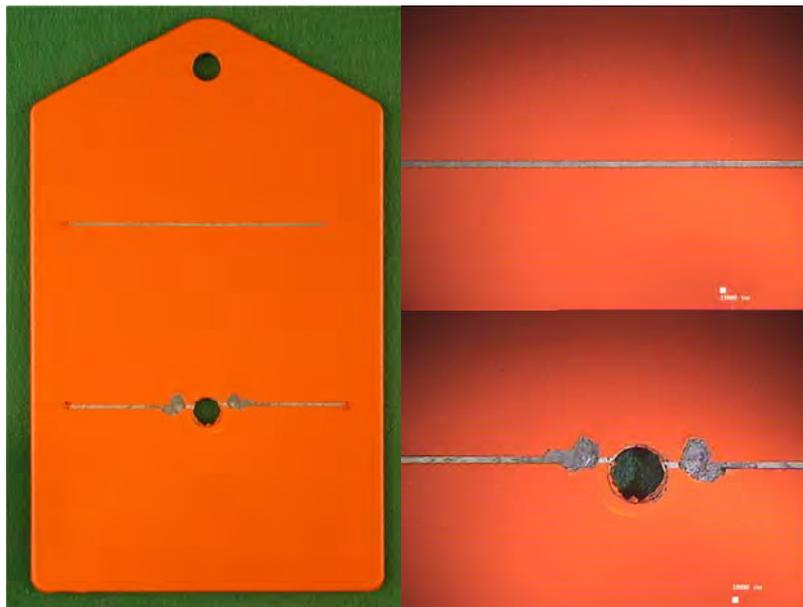
Exposure	Marine	GM9540	SCAB	Mud VICT	VDA
Mean acceleration	1	2,4	1,1	5,6	8,2

Table 19 shows that VDA and the Mud-VICT tests have the highest acceleration, and the SCAB test the lowest.

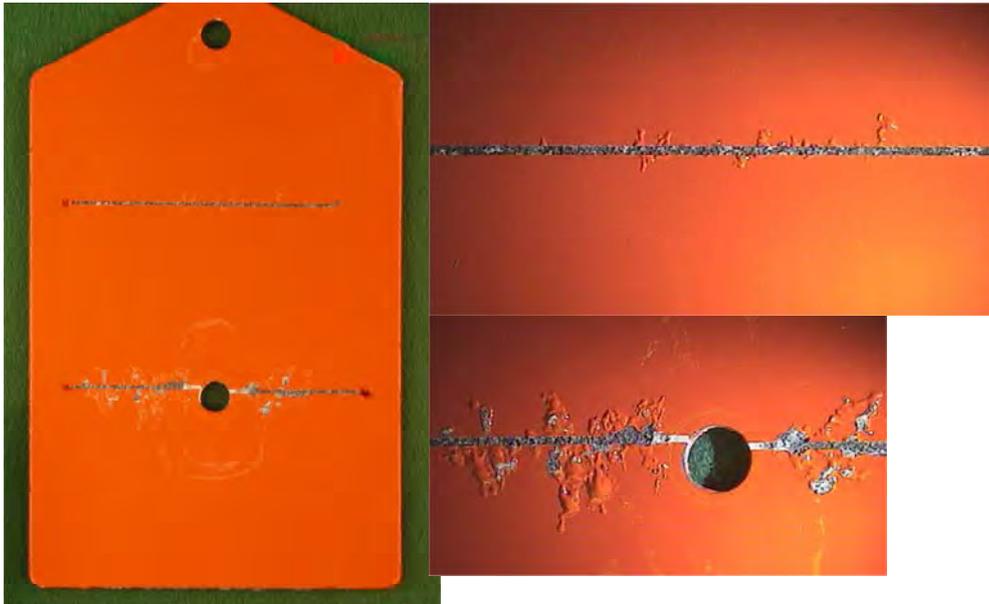
In Figure 48 to Figure 53 panels exposed in the accelerated tests and the field exposures can be seen. All of the panels shown have been treated with Gardobond C722 and powder coat. The appearance of the corrosion attack varies a lot between the different tests.



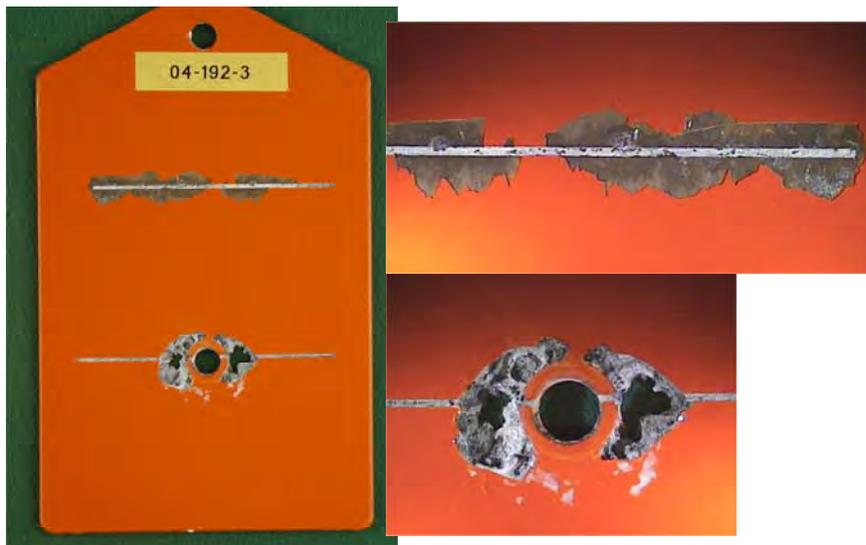
*Figure 48: Panel treated with Gardobond C722 and powder coat, exposed to GM-9540P test for 40 days.*



*Figure 49: Panel treated with Gardobond C722 and powder coat, exposed to SCAB test for 3 months.*



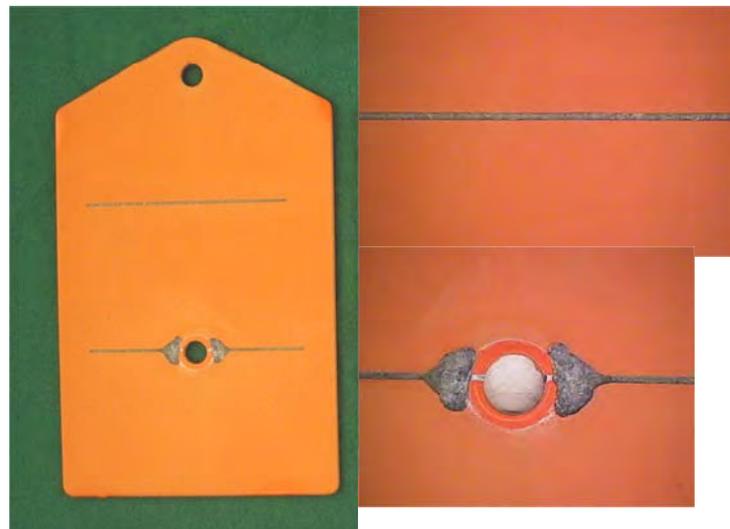
*Figure 50: Panel treated with Gardobond C722 and powder coat, exposed to Mud VICT for 6 weeks.*



*Figure 51: Panels treated with Gardobond C722 and powder coat, exposed to VDA for 10 weeks*



*Figure 52: Panel treated with Gardobond C722 and powder coat, exposed in the mobile exposure for 1 year.*



*Figure 53: Panel treated with Gardobond C722 and powder coat, exposed at Bohus Malmön for 1 year.*

As expected the panels exposed for the VDA test the panels is the most affected panels (*Figure 51*). At the lower of the two scribes the corrosion have even penetrated the panel, the top scribe is also heavily affected by corrosion, with detachment of the powder coat. In the GM test (*Figure 48*), corrosion have affected the top scribe, with detachment of the powder coat. The lower of the two scribes has bimetallic corrosion in the vicinity of the fastener, but the rest of the scribe is unaffected. The panels exposed in the SCAB test (*Figure 49*) are the least affected of the four panels shown. The panels show no attack on the upper scribe but shows attacks on the lower scribe in the vicinity of the fastener. The panels exposed to the Mud VICT (*Figure 50*) shows filiform corrosion attacks, both on the top and the lower of the two scribes. The bi-metallic corrosion in the vicinity of the fastener is not that severe in the case of panels exposed for the mud-VICT test. The filiform corrosion attacks is probably explained by the artificial road dirt, or mud, that is applied on the panels in the Mud-VICT test. The mud keeps a constant high moisture level close to the scribe, which favours the growth

of filiform corrosion. The corrosion on the two panels exposed in the marine and the mobile field exposures (*Figure 52* and *Figure 53*) shows similar corrosion attacks, the top scribe is not affected in the two cases. On the lower scribe we can see bi-metallic corrosion in the vicinity of the fastener, but the rest of the scribe is unaffected, this is valid for both the marine field exposure and the mobile exposure. Just looking at the appearance of the corrosion attacks, it's seems that the SCAB test shows the closest similarity with the two field exposures.

## 5 CONCLUSIONS

The project has shown that the product quality can be improved, and that the production cost and environmental load can be decreased. This can be achieved by fairly small efforts. In detail it has been shown that:

- The AM-converter has the potential to reduce both energy and metal consumption resulting in a more cost effective way of melting magnesium. The melt temperature will also be more uniform inside the furnace.
- Test with the new cover gas system called AM-cover resulted in improved protection compared to the conventional system SF<sub>6</sub> and a more environmental friendly production of magnesium. It is though uncertain if the use of AM-cover is more cost effective compared to the SF<sub>6</sub>-system.
- Die casting parameters do influence the amount of surface defects and the mechanical properties. An imported parameter seems to be the intensification pressure, for which a high value is not always the best.
- A high degree of in-house re-circulation is feasible without negative effect on the product quality. The effect on the corrosion properties is though not thoroughly investigated.
- Magnesium panels without pretreatment performed poorly, in both the marine and the mobile field exposures. It is obvious that pretreatment of the Mg-alloy is needed.
- The alternative pretreatment, Alodine 160 and Oxilan Al 500 shows similar good performance compared to the chrome based Gardobond C722 in both the mobile and the marine exposures as well as in the performed accelerated corrosion tests.
- The big difference in corrosion resistance between the different specimens is mainly due to the paint systems and not to the surface treatments.
- The adhesion of the powder coat towards the magnesium surface was better compared with wet paint systems.
- The extra ED coat layer, applied on the powder coated panels, does not seem to have a big affect on the corrosion behaviour or the adhesion of the powder coat.
- Even though the acceleration of the SCAB test is low the appearance of the corrosion attacks shows the closest similarity with the marine and the mobile exposures.

## 6 FUTURE WORK

To increase the use of magnesium the following topics may be further investigated.

How does already implemented magnesium components manage in real life concerning corrosion resistant, mechanical failures and joining techniques. Investigation and mapping involving several different car brands.

Mg-alloys in assembled components. What joining techniques and surface treatment methods are suitable to use.

It has been showed that the oxide is evenly distributed in a die casted component. This could have a large effect on both the mechanical and corrosion properties, surface treatment and the corrosion

Further reduce the production cost by optimizing the die casting process.

External and internal environmental impact. Reduce noise, air and water pollution by using better production method, eg use of dry powder release agent.

Objective comparison between different Mg-alloys regarding corrosion, mechanical and casting properties. Screening or development of testing methods for new magnesium alloys.

Develop and improve tools for design and simulation of magnesium. Build up better knowledge of construction issues.

## 7 APPENDIX

The refereed documents in this chapter are available just for the participants of the project.

1. Förstudie Pressgjutning av magnesium, report
2. Rapport från Finnveden Gjuteri AB angående implementering av AM-converter, report
3. Litteraturstudie skyddsgaser för Mg, report
4. Förslag till begränsad användning av skyddsgas vid magnesiumsmältning, article
5. Delrapportering från försök med skyddsgas för magnesiumsmältning, report
6. Beräkning av smältaåtgång, excel-file
7. Reserapport från besök vid BMW:s produktionsanläggning i Landshut, report
8. Delrapportering från försök med olika grader av återgång vid magnesiumsmältning, report
9. Dragprov av material från återgångsförsök inom VAMP32, report
10. OM-INDEX, report
11. Processing Effects on Hot Tearing Tendencies of Die Cast Magnesium Components, article
12. Vidhäftningsprovning av gjutna Magnesiumartiklar med ytdefekter, report

## 8 REFERENCES

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- 1 .... Conny Gustavsson, Zoltan Tiroler; Förstudie avseende behovet av och förutsättningarna för tillverkning av stora pressgjutna komponenter i magnesium till fordonsindustrin (050401), Swedish Foundry Association
- 2 .... Magnesium use growing in European cars, news from Hydro Magnesium, [www.hydrumagnesium.com](http://www.hydrumagnesium.com), 2005-11-04
- 3 .... Magnesium Die Casting Handbook, NADCA Publication 201
- 4 .... AM-converter: the solution for efficient magnesium melting; Technical Information Sheet (DA0120); Advanced Magnesium Technologies
- 5 .... N.J Rickets, S.P. Cashion, M.T Frost, G.L Dunlop; Replacement of SF6 for the protection of molten magnesium; CRC for Cast Metals Manufacturing (CAST), Australian Magnesium Corporation
- 6 .... Haiping Cao, Magnus Wessén; Processing Effects on Hot Tearing Tendencies of Die Cast Magnesium Components; Jönköping University.
- 7 .... Per Bakke, Dag Ove Karlsen; Inclusion Assessment in Magnesium and Magnesium Base Alloys (970330), Norsk Hydro A/S, Society of Automotive Engineers Inc.
- 8 .... IceTec, "Corrosion of Magnesium", article "Nordic Magnesium Cluster", <http://normac.teknologisk.dk/>
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- 10 ... G. Stenberg, R Berglund, H Ottertun; "Ytbehandling av magnesium", IVF-skrift 98825, Mölndal 1998
- 11 ... N.LeBozec, M. Jönsson, D. Thierry (2004). "Atmospheric corrosion of magnesium alloys: influence of temperature, relative humidity and chloride deposition." Corrosion **60**(4): 356-362.