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# MAGNESIUM DIECASTING ALLOY AJ62X WITH SUPERIOR CREEP RESISTANCE, DUCTILITY AND DIECASTABILITY

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## Abstract

Magnesium diecasting alloys for elevated temperature applications are coming of age. Several research centers and companies have been working on alloy systems based on alkaline earth and rare earth alloying additions to push the limits for the creep performance of Mg-based diecasting alloys.

Noranda's Mg-Al-Sr based alloys have shown superior creep performance and high-temperature performance at temperatures as high as 150-175C and stress levels of 50MPa - 70MPa. The most recent alloy formulation AJ62x (Mg-6Al-2Sr) has in addition shown excellent castability, and superior hot-tear resistance. Based on these attributes AJ62x is positioned well for applications such as transmission cases and oil pans. In this paper, the mechanical properties (creep and tensile) of AJ62x are presented. The high ductility of the AJ62Lx version is an added advantage for this alloy. Lab-scale evaluation of AJ62x shows that the alloy is more resistant to hot-tearing and cracking than all other magnesium alloys and the A380 aluminum alloy and industrial trials indicate that the alloy is highly castable.

## Introduction

The mass of the vehicle has an effect on fuel consumption by affecting rolling resistance, resistance to climbing and acceleration. A fuel consumption target of 3 to 4 L /100Km is being pursued in various countries, in addition to rising customers expectation in terms of performances, comfort and safety. To achieve these divergent targets, the magnesium with a density of 1.71 g/cm$^3$ is a suitable material. New part applications are primarily responsible for the increasing use of the magnesium in the automotive industry. But the growth has been limited to components that used standard die cast magnesium alloys such AZ91D, AM50 and AM60B and are mainly located in interior applications. There are also distinct advantages to using light-weight magnesium in power-train components where large die cast components are used. However, the service temperatures of power-train components are in the 150$^o$C range, which exceed service temperature of standard magnesium die-casting alloys previously mentioned. Several research centers and companies have been working on developing magnesium diecasting alloys with improved high-temperature performance. Alloy systems based on alkaline earth and rare earth alloying additions have tried to push the limits for the creep performance of Mg-based diecasting alloys. Several types of heat-resistant magnesium alloys have been developed to date, including AS, AE, Mg-Al-Ca, Mg-Al-Ca-RE, Mg-Al-Ca-Sr-RE and Mg-Al-Ca-Sr alloys. Unfortunately, many of these alloys suffer from inferior die-castability (Mg-Al-Ca) or have disadvantages in terms of marginal performance improvements (AS, Mg-Al-Ca-RE, Mg-Al-Ca-Sr-RE) and high material cost (AE, Mg-Al-Ca-RE). Mg-Al-Sr alloys offer a good combination of die-castability, creep at 150$^o$C and 175$^o$C, and cost.

Noranda's Mg-Al-Sr based alloys are clearly positioned at the top performance level with superior creep resistance and a first generation alloy formulation Mg-5Al-2Sr (AJ52x) has also shown good castability when the correct process parameters are used. A new alloy formulation with Mg-6Al-2Sr (AJ62x) offers more advantages, that of

1. Superior creep performance
2. High ductility (AJ62LX version)
3. Very good diecastability and hot-tear resistance
4. Excellent corrosion resistance.

In this paper, mechanical (creep, tensile) corrosion (salt-spray) properties and the castability of the alloy AJ62x will be discussed.

## Background

In selecting alloys for a particular application the user needs to consider different criteria such as performance, manufacturability, and cost. Clearly an engine block that sees service temperatures as high as 200 C needs an alloy that can offer superior creep performance, while an oil pan or an engine cradle may utilize a more moderate creep performance. Having an alloy that has the highest creep resistance possible at high temperatures and stress conditions as well as excellent good tensile properties and ductility, castability, cost and recycling is the current challenge of the magnesium industry. Often we have alloys that have good castability but moderate creep resistance (1), or good creep resistance but very challenging castability (Mg-Al-Ca alloys). The user is now faced with electing a few candidate alloys to eventually develop a Mg-based power train component. Having a number of different alloys, however, will create the need for the establishment of alloy technology (data-base, recycling, casting) for many different alloy systems.

Noranda's Mg-Al-Sr alloys give the automotive user the versatility to provide alloy formulations that meet the demands of the various powertrain components from one single alloy system. The AJ52x (Mg-5Al-2Sr) formulation has creep resistance that is significantly better than all other Mg alloys at the 175 C at 50 MPa. Its castability has been industrially evaluated in power-train components and has been found to be castable with simple change of die and melt temperature (2, 3).

Recently an AJ62x (Mg-6Al-2Sr) composition has also been tried and has been found to have the same superior creep performance as the AJ52x but with the added advantage of better castability. AJ62Lx version of this alloy gives excellent ductility as well. The composition ranges of these alloy formulations are given in Table I below. Noranda AJ62x (as well as AJ52x) are recommended for applications such as transmission cases and engine blocks that see high stresses at high service temperatures. On the other hand AJ62Lx is recommended for oil pan, engine cradle and other components requiring moderate creep performance. Alloys still under development such as AJ7xx, AJ8xx compositions will target components requiring slight improvement in creep resistance over the AM and AZ alloys.

**TABE I. AJ ALLOY COMPOSITIONS**

| ALLOY | Al% | Sr | Comments |
|---|---|---|---|
| **AJ62x** | 5.6 - 6.4 | 2.0-2.4 | Superior creep resistance, and good castability, excellent corrosion resistance |
| **AJ62Lx** | 5.6 - 6.4 | 1.7-2.2 | High creep resistance, good castability, high ductility, excellent corrosion resistance |
| AJ52x | 4.5 - 5.5 | 1.7-2.3 | Superior creep resistance, acceptable castability, excellent corrosion resistance (first formulation) |
| AJ7/8x | x | x | Target for moderate creep resistance and exceptional castability, high ductility and strength (future formulation), |

In order to rationalize the alloy use and minimize the number of alloys Noranda's aim is to commercialize only two of the various developmental formulations. These currently are the AJ52x and AJ62x (both of superior creep performance). Among options is also AJ62Lx (high creep performance and high ductility). An AJx (7-8%Al) is also under development to target the applications needing only a small improvement in creep performance. This way one alloy system (Mg-Al-Sr) can meet the demands of the whole power train. This would be similar to the use of the AM alloys based on varying ductility requirements of the applications. In this paper the properties of the AJ62x and AJ62Lx alloys will be presented.

## Experimental Procedures

### Mechanical and Corrosion Testing

All die-cast test specimens required for the mechanical property determination were cold-chamber diecast. AJ62Lx and AJ62x alloys were die cast at Lunt and Meridian. AJ52x and all other magnesium alloys and the aluminum alloy A380 were cold-chamber diecast at Performag (Montreal). Creep testing and tensile testing were carried out at Westmoreland and Noranda according to ASTM B557 and ASTM E8. Salt-spray corrosion test was conducted at Noranda Technology Center according to ASTM B117.

### Microstructural Investigation

Microstructures of diecast samples were investigated with SEM with field emission gun (<150 000x), x-ray energy dispersive spectrometry (EDX) (<5000x) at Noranda Technology Center., Additional investigation via scanning transmission electron microscopy (STEM) (<300 000x) was carried out at Ecole Polytechnique de Montreal. Both EDX and parallel electron energy loss spectrometry (PEELS) were used.

### Hot-Tear Resistance Testing

Hot-tear resistance testing was carried out at Noranda according to a test method developed by Noranda Technology Centre (4, 5) that is a modification of a method used for aluminum alloys (6). The test involves the casting of the alloys into a mold that has cavities to produce four constrained rods of varying lengths (Fig. 1). Cracks are induced due to the constraining of the rods during solidification. A rating system based on the severity and the location of the crack determines the hot-tear susceptibility of the alloy. For the tests, all alloys were cast with a $100^{o}C$ superheat above their liquidus temperatures.

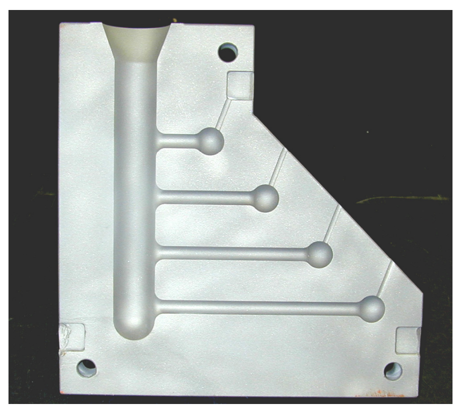


Figure 1. Hot-tear resistance-test mold

### Industrial Casting Trials

Industrial casting trials were carried out at various die casters in North America and Europe. The diecastability was evaluated qualitatively and compared to other alloys cast with the same machines and dies.

## Properties of AJ Alloys

### Creep

The creep resistance of the various alloys is shown in Table II. Tensile creep and compressive creep rankings of the alloys show different trends. At 150 C and a 50 MPa stress the tensile creep deformation after 200 hours can be quite comparable in die cast AJ, AE, AS and even the aluminum 380 alloy. At 175 C and 50 MPa the differences in creep resistance of the alloys become more clear. AJ52x and AJ62x alloys are close contenders to the aluminum A380 with about 0.1% creep deformation while the AE42 alloy shows four times more creep deformation. Tensile creep data at 70 MPa/175C have been presented by Showalter et al (1) and is also provided in Table II for comparison with other alloys.

**TABLE II. TENSILE CREEP OF DIECAST ALLOYS**

| ALLOY | % Creep @ 50 MPa, 200 hrs | | % Creep @ 50 MPa, 500 hrs | | % Creep @ 70 Mpa, 200 hrs (Ref 1) |
|---|---|---|---|---|---|
| | **150 C** | **175 C** | **150 C** | **175 C** | **175 C** |
| AJ52x | 0.04 | 0.05 | 0.03 | 0.09 | 0.14 |
| AJ62x | 0.05 | 0.05 | - | - | - |
| AJ62Lx | 0.13 | 0.29 | - | - | - |
| AE42 | 0.06 | 0.33 | 0.08 | 0.44 | 0.18 |
| AS41 | 0.05 | 2.48 | 0.07 | - | - |
| AS21x | 0.19 | 1.27 | - | - | 8.95 |
| MR153 | - | - | - | - | 4.01 |
| AZ91D | 2.7 | * | 6.35 | - | - |
| A380 | 0.08 | 0.04 | 0.10 | 0.05 | 0.22** |

*failed after 80 hrs **A383 alloy

The compressive creep mode, which is more representative than tensile creep, of the stress conditions in bolted assemblies of power train components, aluminum 380 alloy has the highest resistance to deformation with only 0.03%. AJ alloys outperform all other magnesium alloys such as AE42, AS41, AS21x and the AZ91D. Clearly AJ alloys AJ62x and AJ52x demonstrate significantly better creep performance than all the other magnesium die casting alloys. Bolt-load retention data on alloys presented by Showalter et al (1) is also given for comparison in the table.

**TABLE III COMPRESSIVE CREEP IN DIECAST ALLOYS**

| ALLOY | % Compressive Creep @ 150 C, 70 MPa, 200 hrs | % Bolt-Load Retention 70 MPa, 100 hours (Ref 1) | |
|---|---|---|---|
| | | **150 C** | **175 C** |
| AJ52x | 0.24 | 73% | 49% |
| AJ62x | 1.73 | - | - |
| AJ62Lx | - | - | - |
| AE42 | 2.16 | 65% | 50% |
| AS41 | 6.13 | - | - |
| AS21x | 3.97 | 55% | 29% |
| MR153 | - | 42% | 11% |
| AZ91D | 21 | - | - |
| A380 | 0.03 | - | 81% * |

*A383 alloy

**Tensile Properties**

Room temperature and high temperature tensile properties of the aj alloys are given in table iv. All aj alloys have uts and ys that are higher than all other alloys at all temperatures. The mr153 alloy has slightly higher yield strength at the higher temperatures. The AJ62Lx has the UTS and the elongation. The versatility of the AJ alloys is seen in this trend as well. The same alloy system with a slight modification in composition is able to provide a high ductility alloy in addition to improved creep performance.

**TABLE IV. TENSILE PROPERTIES at 20 C**

| Tensile Properties at 20C | | | |
|---|---|---|---|
| **ALLOY** | **UTS, MPa** | **YS, MPa** | **%E** |
| **AJ62Lx** | **276** | **153** | **12** |
| **AJ62x** | **240** | **143** | **7** |
| AJ52x | 212 | 134 | 6 |
| AE42 | 220 (230) | 128 (145) | 10 (11) |
| AS41 | 197 (215) | 136 (140) | 4 (6) |
| AS21x* | 210 | 121 | 5.5 |
| AZ91D | 204 (240) | 139 (160) | 3.1 (3) |
| MR153* | 197 (250) | 157 (165) | 2.2 (5) |
| A380 | 290 (290) | 155 (180) | 3.2 (3) |
| **Tensile Properties at 150 C** | | | |
| **ALLOY** | **UTS, MPa** | **YS, MPa** | **%E** |
| **AJ62Lx** | **166** | **116** | **27** |
| **AJ62x** | **163** | **108** | **19** |
| **AJ52x** | **163** | **110** | **12** |
| AE42 | 140 (157) | 88 (100) | 23 (20) |
| AS41 | 153 (155) | 94 (95) | 17 (24) |
| AS21x | 130 | 87 | 20 |
| AZ91D | 169 (157) | 105 (108) | 16 (23) |
| A380 | 251 (257) | 148 (159) | 6.4 (7) |
| **Tensile Properties at 175 C** | | | |
| **ALLOY** | **UTS, MPa** | **YS, MPa** | **%E** |
| **AJ62Lx** | **143** | **109** | **27** |
| **AJ62x** | **143** | **103** | **19** |
| **AJ52x** | **141** | **100** | **18** |
| AE42 | 121 (130) | 81 (91) | 23 (23) |
| AS41 | 127 (127) | 85 (85) | 19 (25) |
| AS21x | 110 | 78 | 23 |
| AZ91D | 138 | 89 | 21 |
| MR153* | 139 | 113 (110) | 3.4 |
| A380 | 248 (228) | 154 (148) | 7.1 (10) |

* data from Ref 1 **A383 alloy values in brackets are IMA, AA or supplier information.

**Corrosion**

Salt-spray corrosion resistance of the alloys is given in Table V. AJ alloys have exceptional corrosion resistance. Tolerance levels for the Fe, Ni, Cu contaminants of the AJ alloys are similar to AM alloys as shown in Table V.

**TABLE V. CORROSION RESISTANCE**

| ALLOY | Salt-Spray Corrosion Rate (mg/cm$^2$/day ) |
|---|---|
| AJ62Lx | 0.04 |
| AJ62x | 0.11 |
| AJ52x | 0.09 |
| AE42 | 0.21 |
| AS41 | 0.16 |
| AZ91D | 0.10 |
| A380 | 0.34 |

## Microstructure of AJ Alloys

Microstructure of AJ alloys depends on the amount of Al and Sr. For alloys AJ52x and AJ62x where the Al/Sr ratio is approximately 2-3 are characterized with two types of intermetallics as seen in Fig. 2. Type A intermetallic is a coupled eutectic phase which is $AL_4Sr$, while the Type B phase is a bulky (divorced eutectic type) designated as $Al_3Mg_{13}Sr$. The ratio of bulky type B phase to type A is higher in AJ52x than in AJ62x. The bulky phase has a contribution to very high compressive creep resistance up to 350 C.

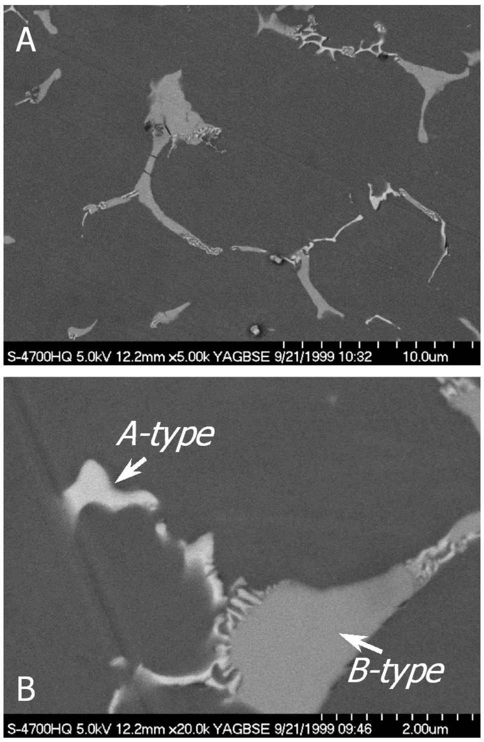



Fig. 2.STEM micrograph showing the two types of intermetallics in AJ52x and AJ62x alloy. Type B is the bulky intermetallic contributing very high creep performance up to 350 C.

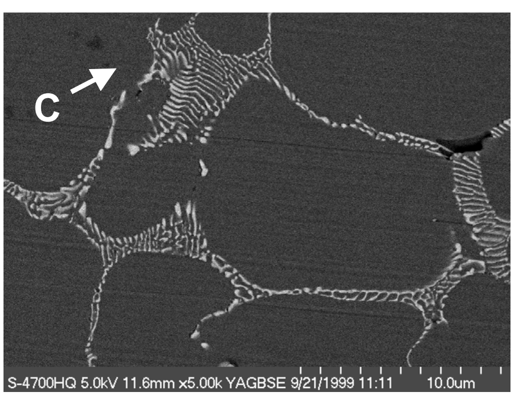



Fig. 3. STEM micrograph showing the lamellar $AL_4Sr$ intermetallics in AJ62Lx alloy. This intermetallic contributes to the high ductility, good castability and strength as well as good creep resistance.

The AJ62Lx, which is the high ductility alloy. is characterized predominantly with a single type phase which is lamellar (coupled eutectic) as seen in Fig. 3. This phase was initially tentatively designated as $Al_{12-Y}$ Mg $_{17-X}Sr_{X+Y}$ or $Al_{10}Mg_{13}Sr$. Subsequent TEM analysis determined that this phase was also $Al_4Sr$. This phase imparts both good creep resistance and high ductility to alloy as well as excellent castability, hot tear-resistance and tensile strength.

## Castability

Castability is influenced by a number of factors that are either alloy dependent or process dependent. Alloy dependent parameters include feeding characteristics (i.e. fluidity), susceptibility to hot-tearing and cracking, freezing range, shrinkage and thermal properties (heat capacity, thermal conductivity) while process dependent factors are comprised of casting parameters and die design considerations. A castability index is under development by Noranda for assessing "a priori" some of the alloy dependent factors and is discussed elsewhere (4,5). In this paper hot-tear resistance of the alloys is discussed.

### Hot-Tear Resistance

The hot-tear resistance of the magnesium alloys evaluated is shown in Table VI. The highest hot-tear susceptibility is observed in the AE42 alloy and the lowest in the AJ62x alloys. Fig. 4 shows a hot-tear test casting made with an AJ62Hx alloy and Fig.5 shows hot-tears produced in an AS41 alloy casting.

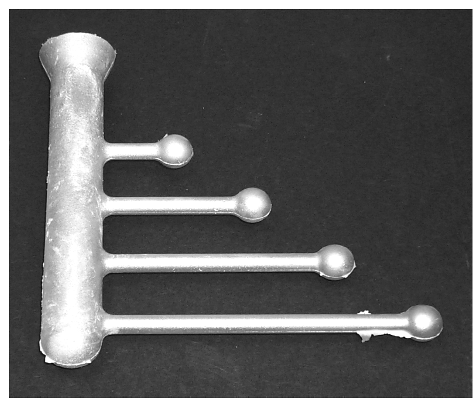


Fig. 4. Casting produced with an alloy having high resistance hot-tearing

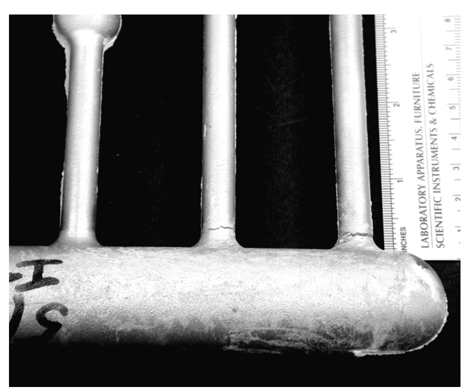


Fig. 5. Tears in a casting produced with an alloy having low resistance to hot-tearing**.**

**Table VI. Hot-Tear Ratings of Various Alloys**

| Alloy | Average Hot Tear Rating* |
|---|---|
| **A380** | 2 |
| **AZ91D** | 20 |
| **AZ91E** | 14 |
| **AM50A** | 44 |
| **ITM alloy (0.8%Ca)** | 61 |
| **AJ50x (0.2Ca, 0.5Sr)** | 45-60 |
| **AS21** | 69 |
| **AS21x** | 27 |
| **AS41B** | 82 |
| **AE42** | 94 |
| **AJ51x** | 35-50 |
| **AJ52x** | 24 |
| **AJ53x** | 5 |
| **AJ62x** | 0 |
| **AJ62Lx** | 0 |

*A lower number means less susceptibility to hot tearing

**Industrial Die Casting Trials**

Several diecasting component trials have been conducted in North America and Europe with the AJ alloys. The first generation AJ52x alloys were diecast as valve covers, an oil pan and other automotive components weighing from 2 to 12kg. The valve cover in Figure 6.a and the oil pan in Figure 6.b were diecast at Spartan Light Metal Products using a cold chamber machine.

Fig. 6.a. Valve-cover cast in AJ52x at Spartan Light Metal Products with very good results.

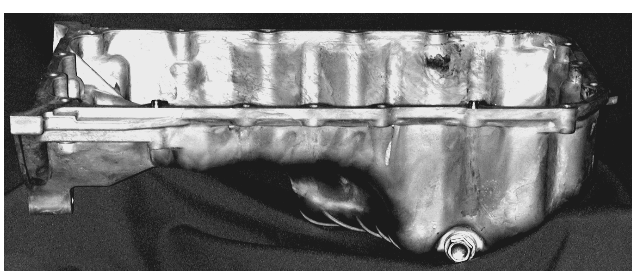
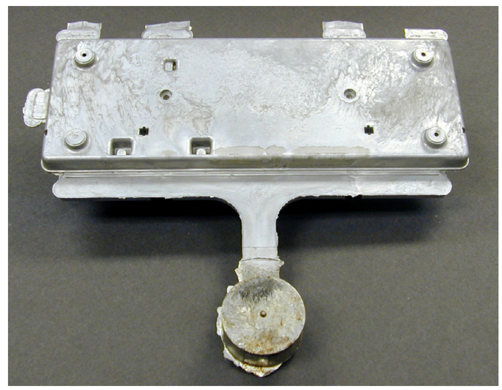


Fig. 6.b. Oil pan cast in AJ52x at Spartan Light Metal Products with very good results.

A medium-walled powertrain component was diecast in Europe using AJ52x. After some optimization of the diecasting process (see table VII), excellent casting soundness (no tears, no feeding problems or internal shrinkage) was obtained and confirmed through fluoroscopic analysis of 50 consecutively cast parts. For confidentiality reasons the part cannot be identified.

Differences in the castability of AJ52x and AJ62x were evaluated at Lunt Manufacturing. The die cast part, called a "Motorola cover", used for the testing is a thin-walled casting produced in an unheated die (Fig. 7). The unheated die gave an opportunity to compare castability under the adverse condition of a cold die surface. Because of the cold die surface the AJ52x experienced certain difficulties that could have been remedied if it were possible to heat the die. The main difficulties were die sticking and cracking. The AJ62Lx alloy, however, demonstrated very good castability using similar process parameters.



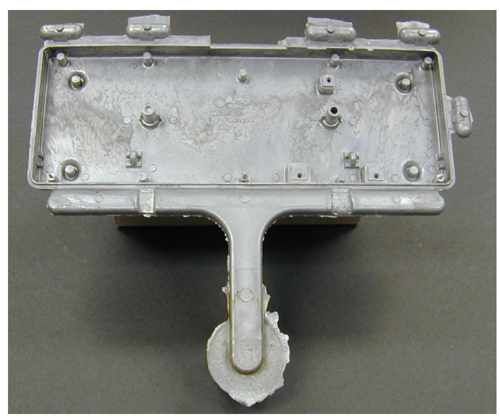


Fig.7. Motorola cover cast with AJ62Lx at Lunt Manufacturing.

AJ62Lx and AJ62x alloy die casting trials were also carried out on powertrain components in North America and Europe. Very good castability was observed in these alloys with no die-sticking or cracking tendencies, good fluidity and hence good die filling. (Table. VIII). Recommended casting parameters for AJ62x alloys are given in Table VII. Many power-train development trials are currently underway with the AJ alloys. Among those that can be mentioned are the EUCAR Mg-Engine and the USCAR power-train programs.

**TABLE VII. DIECASTING GUIDELINES FOR AJ ALLOYS**

| PARAMETER | RECOMMENDED |
|---|---|
| **Die Surface temperature** | **AJ52x** : 300-350 °C<br>**AJ62x** : 250-300 °C |
| **Metal temperature** | 710-720°C |
| **Gate area** | 30-50% greater than Al |
| **Gate velocity** | Low end of North American Die Casting Association (NADCA) recommendations |
| **Fill time** | Low end of NADCA recommendations |
| **Cycle time** | Short to maintain die temperature |
| **Shot sleeve** | Heated/high fill percentage, short dwell time before injection |
| **Draft** | Generous where possible |
| **Ejection** | As early as possible to allow free contraction |

**TABLE VIII. CASTABILITY RATING OF AJ ALLOYS**

| LLO | ie Stickin | rackin | Fluidity | Overall Rating |
|---|---|---|---|---|
| **AJ51x** | low | high | moderate | fair |
| **AJ52x** | moderate | moderate | good | Good. If recommended parameters are used very good castability can be obtained. |
| **AJ62Lx** | Very low | Very low | Similar to AM60 | Very good |
| **AJ62x** | Very low | Very low | Similar to AM60 | Very good |

## Conclusions

1. AJ alloys AJ52x and AJ62x have superior creep performance surpassing all other magnesium alloys at high temperatures (150-175 C) and high stresses (50-70 MPa).
2. AJ62x alloys have the highest tensile properties of all magnesium alloys tested (both room temperature and elevated temperature). AJ62Lx alloy has very substantial ductility.
3. Corrosion resistance of AJ alloys is excellent. The alloys show salt-spay corrosion resistance equal to or better than AZ91D.
4. AJ62x alloys have exceptional resistance to hot-tearing and cracking. The hot-tear tendency is even lower than that of aluminum A380 alloy.
5. The diecastability of AJ62x alloys is very good, and superior to AJ52x alloy.
6. AJ62x alloys are positioned extremely well for use in automotive power train components.


## Acknowledgement

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