Magnesium Alloy Research

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Magnesium Alloys for Space Hardware Design

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I. Abstract

There have been advances in magnesium alloy development that NASA has not taken into consideration for space hardware because of a lack of test data. Magnesium alloys offer excellent weight reduction, specific strength, and deep space radiation mitigation. Traditionally, magnesium has been perceived as having too poor of a flammability resistance and corrosion resistance to be used for flight. Recent developments in magnesium alloying has led to the formation of two alloys, WE43 and Elektron 21, which are self-extinguishing and significantly less flammable because of their composition. Likewise, an anodizing process called Tagnite was formulated to deter any concern with galvanic and saltwater corrosion. The Materials Science Branch at Kennedy Space Center is currently researching these new alloys and treatments to better understand how they behave in the harsh environment of space. Successful completion of the proposed testing should result in a more thorough understanding of modern aerospace materials and processes, and possibly the permission to use magnesium alloys in future NASA designs.

II. Introduction

There have been many integral advancements in magnesium alloying and processing in the past decade. Although structural magnesium products have been used for over a hundred years, the metal industry has only recently "seen a resurgence in the use of magnesium and its alloys in an increasing number[1]." Many of these new developments are targeted for aerospace applications, but NASA has not taken them into consideration because of a lack of materials-related test data.

Traditional magnesium alloys are discarded for aerospace use for a couple of perceived issues. These off-the-shelf alloys are infamous for being flammable, and if they do ignite, they are very difficult to extinguish. There is also an overwhelming concern for corrosion control with magnesium because of its high reactivity on the galvanic scale and its poor performance in saltwater environments. Because of these two characteristic drawbacks, magnesium alloys tend to be overlooked during the material selection process of a flight hardware component.

Despite these design obstacles, magnesium alloys offer great potential in certain applications. Magnesium is the lightest of all structural metals with a density of about one third that of aluminum. In secondary structural designs, magnesium becomes an ideal candidate because of its weight reduction, in turn increasing the fuel efficiency of a launch vehicle or spacecraft. Magnesium alloys also boast one of the best strength to density ratios of any metal[2]. A high specific strength is a fundamental criteria for use as a primary structural material in the aerospace industry. Another important trait of some of these alloys is their ability to mitigate deep space secondary radiation exposure of up to 30% less than typical structural metals such as aluminum. This significant reduction in radiation will be of increasing importance once deep space exploration starts to become a reality.

It is evident that the two primary disadvantages of magnesium are overshadowing the benefits of implementing these metals in NASA designs. Fortunately, the recent improvements in magnesium alloying and processing and utilization in other industries has redressed both these major issues. Magnesium Elektron has developed several high-grade magnesium alloys that are specifically targeted for aerospace applications. The alloying composition enables the metal to be self-extinguishing and limits its flammability. Advances in these new alloys sparked Tagnite to develop more effective anodic treatments that have been specially formulated for magnesium. This anodizing process greatly improves the corrosion resistance of magnesium that traditionally had limited use in harsh environments.

These recent developments in magnesium have mostly remained unnoticed at NASA; however, the potential of these new advanced alloys should not be overlooked. Currently, the Materials Science Branch at Kennedy Space

Center has been working on an internally-funded research project to study high-grade magnesium alloys that are capable of these desired properties. Tests are being performed to meet the requirements of NASA-STD-6016 “Standard Materials and Processes Requirements for Spacecraft”. Successful completion of the proposed research should result in a more thorough understanding of magnesium alloys for space applications, and possibly the permission to use magnesium alloys in future NASA designs.

III. Background

To fully understand the advancements in modern magnesium alloying, a full range of mechanical tests and metallographic examination must be conducted. Three wrought magnesium alloys were the focus of the project: AZ31B-H24, WE43-T6, and Elektron 21-T6. The AZ31 is a general purpose alloy that has been used for 50 years now, whereas the WE43 and Elektron 21 are two alloys recently created by Magnesium Elektron that pass the Federal Aviation Administration flammability rating. Throughout the project, these magnesium alloys will be tested in a variety of ways alongside the typical aerospace grade 7075-T6 aluminum and 304 stainless steel as a baseline comparison. Likewise, some of the magnesium specimens will be anodized using a Tagnite process to be compared to the base material. Each material will be thoroughly tested in order to fully characterize the corrosion resistance, flammability resistance, mechanical properties, and microstructure.

At the forefront of the testing conducted under this project is material characterization and identification. A sampling of each alloy will be cross-sectioned, mounted, and polished to view the general microstructure and compare to published microstructure images. Similarly, electrical conductivity testing and Rockwell hardness testing will be conducted to verify the temper of each alloy using ASTM E1004 and ASTM E18 respectively. For sake of completion, specimens will undergo tensile testing according to ASTM E8 as well. Yield strength, ultimate tensile strength, and percent elongation will all be recorded to further characterize the base material properties.

A large focus of the testing will be to validate the corrosion resistance of the high caliber magnesium alloys in comparison to the standard magnesium, aluminum, and stainless steel alloys. Several specimens of each alloy will be stress corrosion crack tested according to the MSFC-STD-3029 “Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments”. In this test standard, specimens are loaded at 75% of the yield strength in a three-point bend fixture. They are held at this stress for 1000 hours in a 5% salt fog chamber and then microscopically analyzed to determine if stress corrosion cracking occurred. A group of the magnesium specimens will be coated in Tagnite with the focus on understanding how resistant this particular anodic coating is on magnesium. In addition, specimens of each alloy will be tested for long term saltwater environment corrosion at the Beach Site Test Facility at Kennedy Space Center. The key measurement for this multi-month test is the mass loss of the individual specimen. Just like the stress corrosion crack tests, the Beach Site testing will include some magnesium specimens that will have a Tagnite anodizing.

Finally, specimens of each designation will be tested to the NASA–STD-6001B “Flammability, Offgassing, and Compatibility Requirements and Test Procedures” Test 17 to determine flammability resistance. This set of tests will determine the length of ignition propagation, thereby determining whether the new magnesium alloys are able to extinguish quicker than traditional alloys. A variety of diameter sizes will be tested to find the minimum thickness that a particular alloy must be to pass the qualifications for this test standard, that is the thickness at which ignition will not occur.

IV. Results and Discussion

All five alloys were tensile tested and the resulting stress strain data is shown in Table 1-5. Data of particular interest includes the yield strength, ultimate tensile strength, and elongation. Comparisons between published data and the experimentally determined data in Table 1-5 overlap and verify the alloying content.

Table 1 WE43 Tensile Test Data

Specimen Label	Modulus (Automatic Young's) [MPa]	Tensile strength [MPa]	Yield Strength (Offset 0.2 %) [MPa]	Elongation after failure (%)
WE43-T-1	42911	265	170	9.4
WE43-T-2	48508	265	165	9.8
WE43-T-3	41370	259	162	7.7
WE43-T-4	58428	240	167	5.4
WE43-T-5	46043	258	166	14.1
WE43-T-6	44179	262	167	9.9
WE43-T-7	54499	261	173	12.1
WE43-T-8	49893	262	179	9.7
WE43-T-9	42428	258	177	12.4
WE43-T-10	41432	259	169	12.7
Average	**46969.1**	**259**	**169**	**10.3**

Table 2 Elektron 21 Tensile Test Data

Specimen Label	Modulus (Automatic Young's) [MPa]	Tensile strength [MPa]	Yield Strength (Offset 0.2 %) [MPa]	Elongation after failure (%)
E21-T-1	49309	275	152	8.5
E21-T-2	43952	283	162	6.7
E21-T-3	43483	276	151	7.8
E21-T-4	47825	290	165	7.4
E21-T-5	48676	282	159	7.1
E21-T-6	44234	284	156	7.3
E21-T-7	18563	277	177	7.4
E21-T-8	44149	289	155	7.4
E21-T-9	45946	293	161	6.4
E21-T-10	43130	288	161	7.3
Average	**42927**	**284**	**160**	**7.3**

Table 3 AZ31 Tensile Test Data

Specimen Label	Modulus (Automatic Young's) [MPa]	Tensile strength [MPa]	Yield Strength (Offset 0.2 %) [MPa]	Elongation after failure (%)
AZ31-T-1	40309	294	236	15.8
AZ31-T-2	42047	294	205	17
AZ31-T-3	41701	293	196	14.8
AZ31-T-4	42389	294	206	13.8
AZ31-T-5	42511	295	198	15.8
AZ31-T-6	41694	292	206	12
AZ31-T-7	42449	295	207	14.3
AZ31-T-8	42072	294	205	14.9
AZ31-T-9	42115	295	205	15.4
AZ31-T-10	42235	293	196	16.2
Average	**41952**	**294**	**206**	**15.0**

Table 4 7075 Tensile Test Data

Specimen label	Modulus (Automatic Young's) [MPa]	Tensile strength [MPa]	Yield Strength (Offset 0.2 %) [MPa]
AL-T-1	72553	570	494
AL-T-2	70752	564	496
AL-T-3	66392	560	494
AL-T-4	67881	563	495
AL-T-5	72088	562	486
AL-T-6	65475	551	486
AL-T-7	68520	556	489
AL-T-8	68802	560	494
AL-T-9	69124	564	494
AL-T-10	70673	556	487
Average	**69226**	**561**	**491**

Table 5 304 Tensile Test Data

Specimen label	Modulus (Automatic Young's) [MPa]	Tensile strength [MPa]	Yield Strength (Offset 0.2 %) [MPa]	Elongation (%)
CRES-T-2	203267	714	285	0.0
CRES-T-3	194898	704	303	67.8
CRES-T-4	39299	701	300	67.6
CRES-T-5	186377	708	275	67.6
CRES-T-6	206744	696	270	69.2
CRES-T-7	184629	688	266	67.2
Average	**169202**	**702**	**283**	**67.9**

Electrical conductivity and hardness tests are quick and accurate ways to determine the temper or processing conditions of a material. Electrical conductivity was conducted on the 7075 by the eddy current method with a portable probe. Hardness data was gathered through a Rockwell tester. Both 304 and 7075 had hardness values on scale B and can easily be compared to each other. Using the technical standard AMS 2658, it was verified that the 7075 was hardened using a T6 temper.

Table 6 7075 Electrical Conductivity Test Data

Specimen label	Conductivity (%)
AL-1	35.1
AL-2	35.1
AL-3	35.0
AL-4	35.1
Al-5	35.0
Al-6	35.2
Al-7	35.2
AL-8	35.1
AL-9	35.1
AL-10	35.1
AL-11	35.1
AL-12	35.1
AL-13	35.1
AL-14	35.1
AL-15	35.1
Average	**35**

Table 7 7075 Hardness Test Data

Specimen label	**Hardness (HRB)**
AL-1	87
AL-2	88
AL-3	87
AL-4	87
Al-5	86
Al-6	87
Al-7	87
AL-8	85
AL-9	86
AL-10	86
AL-11	87
AL-12	87
AL-13	86
AL-14	87
AL-15	86
Average	**87**

Table 7 304 Hardness Test Data

Specimen label	**Hardness (HRB)**
CRES-1	89
CRES-2	94
CRES-3	88
CRES-4	92
CRES-5	92
CRES-6	89
CRES-7	92
CRES-8	87
CRES-9	87
CRES-10	92
CRES-11	88
CRES-12	90
Average	**90**

The microstructure of the 304 and 7075 was analyzed using a metallograph light microscope. The 304 stainless steel proved difficult to etch correctly, like most austenitic stainless steels. Grain boundaries were not able to be distinguished in these etches. Instead, deep corrosion pits formed on the surface of the steel. Different dilutions and soak times were attempted to improve the quality of the etching. Unfortunately, no combination of factors worked effectively with the Carpenter's Series 300 Etchant. It is recommended to perform electrolytic etching with oxalic acid to yield an adequate microstructure.

The 7075 aluminum was etched with Weck's color etchant, providing very distinguishable grain boundaries. Many hours were spent to refine the process. It was discovered that a soak time of about two minutes in undiluted etchant was the most ideal. Differential Interference Contrast (DIC) lighting was used in effect with the color tint etchant to give the best contrast in grain boundaries. Figure 1 and 2 show the typical microstructure of 7075-T6. Figure 3 depicts an anomaly with the etchant where the etchant leaves a trail of colors behind; however, the grain boundaries are still easily identifiable and match that of Figure 1 and 2.

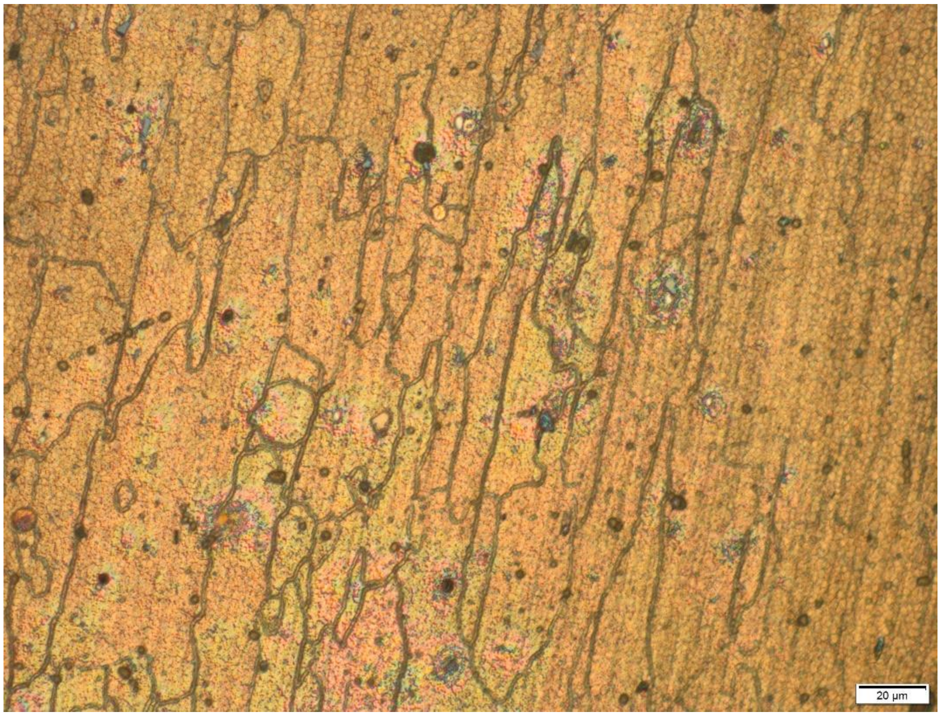

Figure 1 Specimen AL-4 Microstructure, 500X, Weck's Color Etchant, DIC

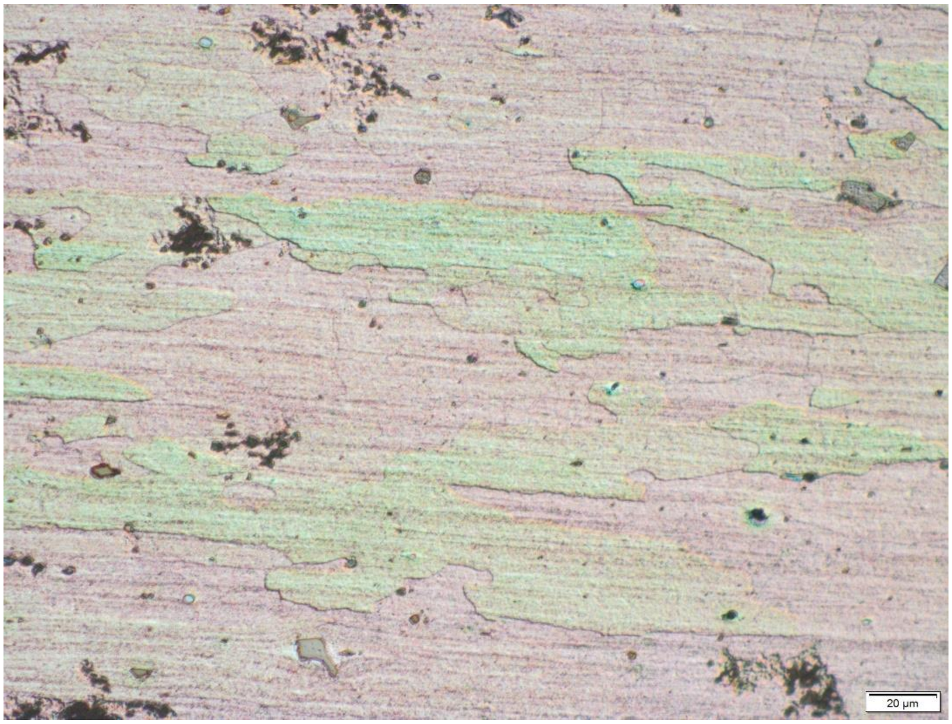

Figure 2 Specimen AL-15 Microstructure, 500X, Weck's Color Etchant, DIC

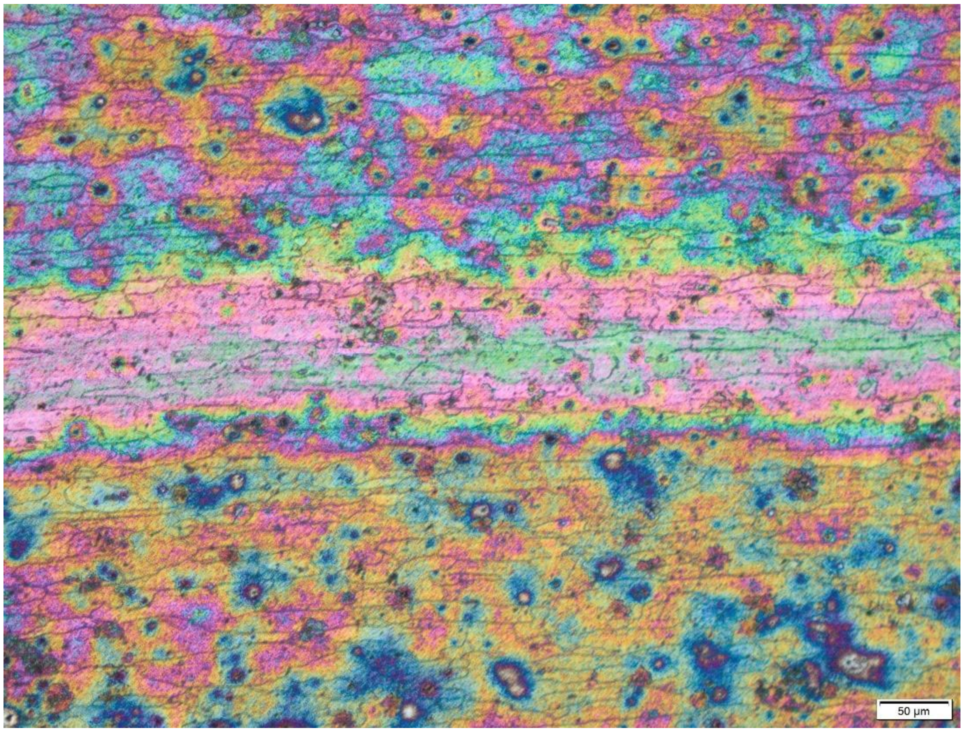

Figure 3 Specimen AL-3 Microstruture, 200X, Weck's Color Etchant, DIC

V. Conclusion

Much of the testing for this research grant still needs to take place before any conclusion can be made about the unique characteristics of these magnesium alloys. However, many of the metallography techniques needed to analyze future samples have been finalized and refined. Likewise, most of the mechanical property testing is completed and is useful to verify the material and temper. Specimens are currently being tested for corrosion and will be finished in about 40 days. Additionally, flammability testing will be conducted soon. The final data analysis will happen shortly after the corrosion and flammability testing are completed.

In reality, this is preliminary research with the goal of peaking the interest of other NASA research groups to carry on a full-scale investigation in these alloys. A more thorough study on these alloys should be conducted before completely qualifying the integration of magnesium alloys in NASA designs. The current ongoing research discloses the fact that there are still many new materials in the aerospace industry that have serious potential at NASA, but have not had enough exposure yet. An abundance of test data on magnesium products may prove to advance the space flight systems at NASA, and in turn, the magnesium industry itself. Ultimately, "the future of wrought magnesium products will be highly dependent on clever alloy design.[1]"

References

[1] Bettles, C., and Barnett, M., *Advances in Wrought Magnesium Alloys: Fundamentals of Processing, Properties, and Applications*, Woodhead Publishing, Cambridge, 2012, pp. xiii.

[2] Ashby, M. F., *Materials Selection in Mechanical Design*, 5th ed., Butterworth-Heinemann, Oxford, 2016, Chaps. 3, 4.