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IDEA

High-Speed Rail IDEA Program

**High-Strength, Lightweight Car Bodies for High-Speed
Rail Vehicles**

Final Report for High-Speed Rail IDEA Project 32

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HIGH-STRENGTH, LIGHTWEIGHT CAR BODIES FOR HIGH-SPEED RAIL VEHICLES

**IDEA Program Final Report
For the period June 2001 Through October 2004
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Table of Contents

ACKNOWLEDGEMENTS	v
ABSTRACT	vi
EXECUTIVE SUMMARY	vii
INTRODUCTION	1
STAGE 1	
CASTING	1
HOMOGENIZATION	2
EXTRUSION AND PROCESSING	2
STAGE 2	
HEAT TREATMENT AND AGING	5
MICROSTRUCTURE	8
MECHANICAL TESTING	11
WELDING	13
CORROSION TESTING	15
STRESS CORROSION CRACKING	16
STAGE 3	
Alloy Down Selection	17
PRELIMINARY CAR BODY DESIGN	17
ANALYSIS OF DESIGN CONCEPT	20
Comparison of Deflection	21
Comparison of S_x at the Midspan Region	22
Comparison of Shear Stress Contour Plots:	22
SUMMARY AND CONCLUSIONS	
ALLOY SELECTION	22
COST	23
DESIGN	23
REFERENCES	23

List of Tables

		Page
Table 1	Chemical Analysis of Cast Billets	1
Table 2	Extrusion and Processing Conditions	5
Table 3	Mechanical Properties of A-Frame Extrusion	12
Table 4	Mechanical Properties of Rectangular Extrusions	13
Table 5	Tensile Strength of Friction Stir Welds	14
Table 6	Results of General Corrosion Testing After 90-Day Exposure	16
Table 7	Results of NAMLT Corrosion Testing	16
Table 8	Mechanical Properties of Typical Aerospace and Marine Al Alloys	23

List of Figures

		Page
Figure 1	Casting furnace at ST2 foundry in Baltimore	2
Figure 2	Extrusion press	3
Figure 3	Section of A-frame extrusion	3
Figure 4	A-frame extrusion dimensions	3
Figure 5	Scalped and homogenized extrusion billets for candidate alloys	4
Figure 6	Rectangular extrusion (a), A-frame extrusion (b)	4
Figure 7	Extrusion stretching	4
Figure 8	Hardness as a Function of Aging at 320°F and 350°F for 6061 “A-frame” Extrusions with and without the Sc Addition	6
Figure 9	Hardness as a function of aging at 350°F for 6061 extruded bar with and without the Sc Addition	6
Figure 10	Hardness as a function of aging at 250°F for 7xSc “A-frame” extrusions	7
Figure 11	Hardness as a Function of Aging at 250°F for 7xSc “rectangular” Extrusion	7
Figure 12	Hardness as a function of aging at 325°F for 7xSc “rectangular” extrusions	8
Figure 13	7xSc-T6 rectangular extrusion [Heat #936] (a) LT-ST 100x, (b) LT-ST 400x, (c) L-ST 100x and (d) L-ST 400x	9
Figure 14	6061-T6 rectangular extrusion [heat #938] (a) LT-ST 100x, (b) LT-ST 400x, (c) L-ST 100x and (d) L-ST 400x	9
Figure 15	6xSc-T6 rectangular extrusion [Heat #940](a) LT-ST 100x, (b) LT-ST 400x, (c)L-ST 100x and (d) L-ST 400x	10
Figure 16	5xSc-H116 rectangular extrusion [Heat #934] (a) LT-ST 100x, (b) LT-ST 400x, (c) L-ST 100x and (d) L-ST 400x	10
Figure 17	Alloy 5456-H116 rectangular extrusion [Heat #932] (a) LT-ST 100x, (b) LT-ST 400x, and (c) L-ST 100x	11
Figure 18	Alloy 7xSc Frame extrusion (#937) showing areas of recombination	11
Figure 19	Location of tensile test specimens for A-frame extrusion	12
Figure 20	FSW assemblies – top surfaces on left, bottom surfaces on right	13
Figure 21	Friction stir welding tool	13
Figure 22	7xSc [Heat #936] friction stir weld	14
Figure 23	Hardness Traverse through FSW in the candidate and baseline alloys (Vickers Hardness)	15
Figure 24	Design for passenger car shells	17
Figure 25	Design for passenger car shells	18
Figure 26	Design for passenger car shells	18

Figure 27	Full scale aluminum alloy integrally stiffened extrusion at Cameron Forge, Texas (Figure from Final Report, Development and Manufacture of Cryogenic Tank, National Launch System, Advanced Development Program #3106, Martin Marietta, 1993)	Page 19
Figure 28	Aluminum alloy integrally stiffened extrusion	19
Figure 29	Net shaped integrally stiffened extrusion panel from Russian Aluminum Company	20
Figure 30	Preliminary design for car body shell using ST2 net shaped extrusion concept.	20
Figure 31	Geometry, boundary conditions and loading of the analysis.	21
Figure 32	Deflected Shape of the 7xSc alloy extruded section with no Weld.	21
Figure 33	Deflected Shape of the 6061-T6 extruded Section with Middle Weld.	21

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ABSTRACT

Surface Treatment Technologies, Inc. (ST2) evaluated high strength alloys combined with novel design approaches and advanced joining techniques to develop crash resistant high speed passenger rolling stock concepts. The use of high strength aerospace aluminum alloys in railcar construction has historically been limited by joining and corrosion issues. The metallurgical evaluation conducted in this project showed that aluminum alloys containing scandium have strengths comparable to high strength aerospace alloys with corrosion resistance and weldability comparable to alloys typically used in rail car construction. In addition, the resistance to recrystallization imparted by the scandium addition allows these high strength alloys to be fabricated into complex shapes. Designers can use these high strength alloys to increase performance and safety of passenger rolling stock. This work also evaluated using integrally stiffened extruded panels to replace built up and welded structures currently used. The use of integrally stiffened panels joined using the friction stir welding process can reduce manufacturing cost and improve safety and reliability. A path for manufacturing extruded integrally stiffened aluminum scandium alloy panels was established. As a follow-on to this project ST2 has initiated discussions with car builders to incorporate these design concepts and alloys into passenger rolling stock systems.

Key Words: rail passenger cars; high-speed rail; passenger car construction; aluminum-scandium alloys, friction stir welding; scandium; aluminum scandium alloys

EXECUTIVE SUMMARY

In this project Surface Treatment Technologies demonstrated a novel approach for building safer high performance high speed passenger car shells. The thrust of this program was to evaluate the potential of using scandium containing aluminum alloys in combination with advanced joining and fabrication approaches to increase performance, reduce operating costs and improve safety of high speed passenger rail vehicles. This approach combined three key elements 1) light weight high strength weldable aluminum scandium alloys 2) Advanced joining techniques (Friction Stir welding) and 3) advanced processing to fabricate net shaped panels. This study was intended to select the optimal scandium-containing aluminum alloy composition for high speed passenger rail applications. At present, aluminum scandium alloys are seeing widespread use in “High Tech” sporting good products such as ball bats, bicycles, golf clubs and lacrosse poles. In addition, scandium-containing aluminum alloys were scheduled to be used in military aerospace systems in the former Soviet Union. Although this family of alloys is available commercially, they have not been optimized or qualified for use in passenger vehicles.

As was pointed out by Zehnder (1), rail cars are typically designed for a 30 year life. Thus, the rail industry is very cautious when it comes to new materials. Trade offs between cost and performance dictate the materials used in construction of passenger vehicles. Although aluminum alloys are more expensive than steel they are selected for there low density. According to Hauser (2), the New York, New Haven and Hartford railroad used aluminum seat frames on lightweight passenger rail cars back in 1894. Developmental work continued and the first two main-line all aluminum passenger railroad cars were exhibited at the 1933-35 Chicago Worlds Fair. At present conventional Al-Mg-Si 6XXX alloys (e.g. 6061) and Al-Mg 5XXX alloys (e.g. 5083) are used to fabricate high speed car body shells. High strength Al-Zn-Mg-Cu 7XXX series (e.g. 7075) and Al-Cu 2XXX series (e.g. 2024) aerospace aluminum alloys are not used due to issues associated with poor weldability and corrosion.

Scandium provides the highest increment of strengthening per atomic percent of any alloying element when added to aluminum (3). Small amounts of scandium are very effective at improving mechanical properties and refining the microstructure of wrought aluminum alloys. In addition, scandium additions have been shown to improve weldability of aluminum alloys by reducing hot cracking in the weld region. In the current study we performed a trade-off study to determine if scandium additions would improve the performance of conventional Al-Mg 5XXX and Al-Mg-Si 6XXX alloys and if a scandium-containing Al-Zn-Mg-Cu 7XXX series alloy could be used to fabricate car body shells.

Fabricabilty, mechanical properties, weldability and corrosion resistance were evaluated for candidate and conventional alloys. The ability to fabricate complex extrusions was evaluated for the candidate and conventional alloys using a porthole die. All alloys were successfully extruded using common commercial practices. Metallographic evaluation of the extrusions showed that as expected the Sc addition refined the grain size in the Al-Mg 5xSc alloy and the Al-Zn-Mg-Cu 7xSc. The scandium addition did not refine the grain size in the Al-Mg-Si 6061 alloy. A summary of mechanical properties and corrosion susceptibility for all alloys is shown below.

	Conventional Alloy 5465	Candidate Alloy 5xSc	Conventional Alloy 6061	Candidate Alloy 6xSc	Candidate Alloy 7xSc
Strength (ksi) [YS/UTS]	33/49	40/60	49/53	46/49	76/83
SCC	Passed	Passed	Passed	Passed	Passed
NAMLT (mg/cm ²)	4	46	--	--	--
Corrosion Rate (g/m ² •yr)	-1.02	-1.72	-1.09	-0.63	-1.80
Weld Strength (ksi)	27	35	33	37	70

(YS = Yield Strength; UTS = Ultimate Tensile Strength; SCC = Stress Corrosion Cracking; NAMLT = ASTM test for inter-granular corrosion.)

The key result from this study is the good corrosion resistance and high base metal and weldment strengths observed for the Al-Zn-Mg-Cu 7xSc alloy. These properties in combination with the ease of fabrication lead to its down selection as the optimal composition for high speed rail applications

Advanced design and fabrication techniques were also evaluated as part of the program. Car body shells for passenger cars are fabricated using various approaches including mechanically fastened sheet and stringers. Recent efforts in Japan and Europe have focused on building shells from welded aluminum extrusions. The use of large integrally stiffened extruded panels was evaluated as part of the current effort. In this approach the side walls and top of the car body are fabricated from large, net-shaped scandium-containing aluminum alloy extruded panels. Integrally stiffened extruded panels as large as 8 foot wide by 35 foot long have been fabricated for aerospace applications. The safety of the passenger car shell is greatly improved by removing longitudinal welds currently used to join aluminum extrusions, thereby increasing resistance to side impact. Finite element analysis conducted as part of this program showed that car bodies fabricated using integrally stiffened extruded panels are more resistant to side impact.

1. J. Zehnder, Al in the Rail Transportation Market, *Mat. Sci. Forum*, Vols. 390-402, pp. 3-8, 2002
2. G. B. Hauser, Chapter 16 Railroad equipment, Aluminum Volume II. Design and Applications, ed. Kent R. van Horn, American Society for Metals, 1967
3. Kharakterova et al., *Acta Metall. et. Mater.*, Vol. 42, pp. 2285-2290, 1994.

INTRODUCTION

The goal of this program was to develop high strength aluminum-scandium (Al-Sc) alloys that will increase the performance envelope, improve crash worthiness and decrease the life cycle costs of high-speed passenger train vehicles. In this program, Surface Treatment Technologies (ST2) evaluated the potential of developing high strength aluminum-scandium alloys currently used in sporting good applications to meet the demanding requirements of lightweight high-strength rolling stock. A trade-off study to evaluate performance issues associated with fabricating the main structural components for high-speed passenger vehicle from advanced aluminum-scandium alloys was performed. By comparing these alloys to the conventional ones currently used, it was anticipated that the study would determine if the increased cost per pound of raw materials associated with adding scandium to aluminum is offset by lower fabrication costs, reduced life cycle costs, and increased performance. The results of this preliminary evaluation allowed ST2 to select the optimum alloy to fabricate the main structural components of train vehicles.

The program was divided into three stages. In stage one of the program, suitable candidate and baseline aluminum alloys were selected, cast and extruded. The baseline alloys were an Al-Mg-Si alloy (6061) and an Al-Mg alloy (5456). These alloys are representative of alloys currently used on high-speed passenger vehicles. Candidate alloys included a Sc-modified Al-Mg-Si alloy (6xSc), an Al-Mg-Sc alloy (5xSc) and a weldable Al-Zn-Mg-Cu-Zr-Sc alloy (7xSc). In stage two, optimal heat treatments were developed for the alloys and welding studies were conducted. Mechanical property, microstructure and corrosion data were obtained for the materials during this stage. In stage three, a study to evaluate the performance of the candidate and baseline alloys was performed. This led to a preliminary rail car design that made use of the advanced alloy properties.

STAGE 1

CASTING

A total of 10 billets were cast (2 billets x 5 alloys). Billet numbers, alloy designations and nominal compositions are:

#932-933	5456	Al-5.0 Mg-0.75 Mn-0.10 Cr
#938-939	6061	Al-1.1 Mg-0.30 Cu-0.60 Si-0.20 Cr
#934-935	5xSc	Al-5.9 Mg-0.4 Mn-0.08 Zr-0.25 Ti-0.26 Sc
#940-941	6xSc	Al-1.1 Mg-0.30 Cu-0.60 Si-0.20 Cr-0.12 Sc
#936-937	7xSc	Al-5.2 Zn-1.9 Mg-0.25 Cu-0.20 Mn-0.14 Zr-0.03 Ti-0.12 Sc

A sample was taken from one billet of each heat and sent to Lehigh Laboratories, New Castle, DE, for chemical analysis. Results are shown in Table 1. All billet compositions were within target ranges.

TABLE 1 Chemical Analysis of Cast Billets

Billet No.	Alloy	Mg (wt%)	Mn (wt%)	Cr (wt%)	Zn (wt%)	Cu (wt%)	Zr (wt%)	Si (wt%)	Ti (wt%)	Sc (wt%)
933	5456	5.60	0.59	0.08						
934	5xSc	6.31	0.41				0.09		0.03	0.28
937	7xSc	2.16	0.19		5.25	0.33	0.20		0.03	0.12
938	6061	1.14		0.19		0.34		0.67		
940	6xSc	1.13		0.19		0.34		0.64		0.11

The initial charge for each furnace lot was 120 lbs. This quantity was sufficient to fill two, steel molds, each approximately 6.5" ID x 15" h. The furnace charge was prepared by weighing the requisite amount of constituent-aluminum master alloy or, in the case of aluminum and zinc, primary ingot. A digital scale with a resolution of 0.02 kg was used to weigh the components. The melting furnace utilized induction heating with a 100 kW, 4000 Hz power supply and a graphite crucible (Figure 1). The aluminum ingots were placed in the crucible and heated to approximately 680°C, about 20°C above the melting point. After complete melting of the aluminum, the master alloys were added. The alloying materials were added incrementally and the charge was allowed to recover to at least 680°C before further additions were made. After all the constituents had been added, the temperature was raised to 740-750°C for fluxing.

Oxide inclusions and entrapped gas were minimized via the use of inert gas fluxing. A dry, 99% Ar / 1% SF₆ (sulfur hexafluoride) mixture was used. The gas was injected into the charge with a graphite lance, tipped with a porous nozzle. As the gas bubbled to the top of the melt, oxide impurities were floated to the surface where they could be skimmed off. Similarly, any entrapped gas would tend to diffuse into the rising bubbles of the flux mixture or would be freed to float to the surface due to the mechanical agitation of the process. After removing the dross from the melt surface, the charge was ready for casting.

Each furnace charge produced two cast billets. The steel molds were preheated to remove any residual moisture. Placing the molds adjacent to the furnace during melting allowed them to partially couple with the induction field and slowly warm. After fluxing and skimming, the charge was brought to 710-720°C and poured into the molds. The furnace was tilted via a cable and winch mechanism, allowing close control of the pour rate. The metal was poured so as to allow rapid filling of the mold with as little turbulence as possible. As the metal level approached the top of the mold, the pouring rate was gradually decreased to an amount that would allow continuous feed of the central, shrinkage pipe without overflow. When the top had solidified, the filled mold was removed and the remaining charge reheated to the original casting temperature. The next mold was then filled in a similar manner. After completion, any remaining metal was poured into a spare mold and the crucible cleaned to the extent possible. Upon complete cooling, the crucible was thoroughly cleaned to remove all remnants of the previous heat and then charged for the next casting.



FIGURE 1 Casting furnace at ST2 foundry in Baltimore

HOMOGENIZATION

After cooling, the irregularly shaped billet tops were removed by saw cutting. The billets were stamped with identification numbers and homogenized. Homogenization is a thermal treatment designed to minimize the segregation that is present in all non-equilibrium cooled, cast microstructures. Each billet was placed in an electric, convection oven, heated to the homogenization temperature and held for 15-18 hours. The billets were cooled in the oven via room temperature, forced-air convection. Homogenization temperature for each billet is given below. After homogenization, the billets were sent to a vendor for extrusion.

<u>Billet No.</u>	<u>Alloy</u>	<u>Homogenization Temp.</u>
#938-941	6061, 6xSc	970-980°F
#932-935	5456, 5xSc	920-930°F
#936-937	7xSc	865-870°F

EXTRUSION AND PROCESSING

All extrusion was performed at Aero Space Aluminum Products, Sulphur Bluff, TX, using a Watson-Stillman, 1250 ton, reverse acting press (Figure 2) with a six-inch diameter container. Two shapes were extruded: a 0.5"x 3.5" rectangular bar and a hollow, "A-frame" section, shown in Figures 3 and 4. The A-frame shape was selected to approximate the complex extrusions required on high-speed vehicles. A welding chamber, porthole die was fabricated for this effort. Prior to extrusion, the billets (Figure 5) were machined to final size (nominal 6" OD) and preheated in a holding furnace in proximity to the press. After preheating, the billets were extruded (Figure 6) using the applicable die. The heat-treatable

alloys (6061, 6xSc and 7xSc) were solution heat treated and stretched to straighten, resulting in a T4 temper. The non-heat-treatable alloys (5456, 5xSc) were thermally stabilized and stretched to strain harden (Figure 7). Alloy 5456 was treated to a corrosion resistant H116 temper. The same temper was used for alloy 5xSc. The Al-Mg (5456 and 5xSc) and Al-Zn-Mg (7xSc) alloys required higher pressures and extruded slower than the Al-Mg-Si alloys (6061 and 6xSc).

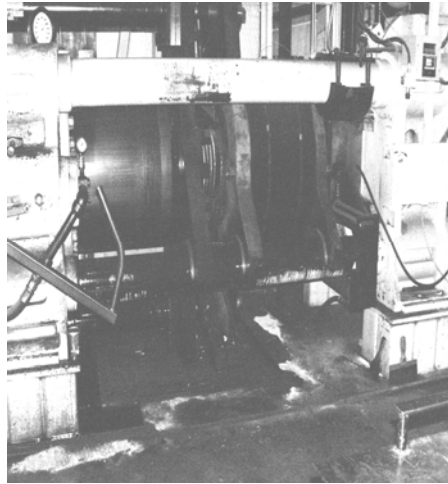


FIGURE 2 Extrusion press



FIGURE 3 Section of A-frame extrusion

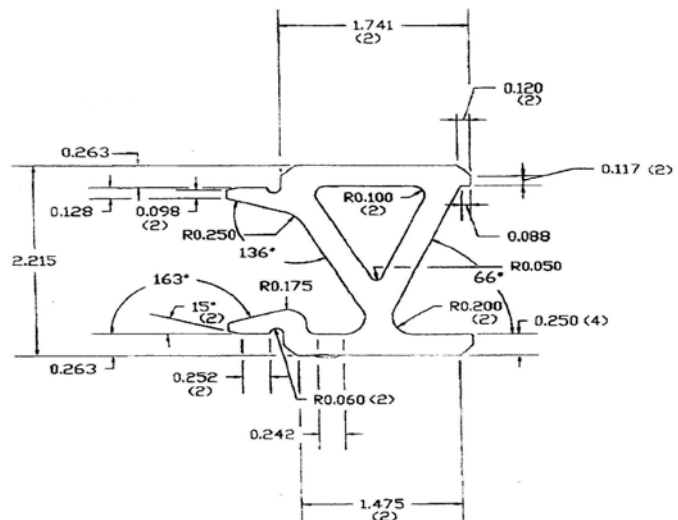


FIGURE 4 A-frame extrusion dimensions



FIGURE 5 Scalped and homogenized extrusion billets for candidate alloys

(a)



(b)



FIGURE 6 Rectangular extrusion (a), A-frame extrusion (b)



FIGURE 7 Extrusion stretching

TABLE 2 Extrusion and Processing Conditions

Billet No.	Alloy	Form ¹	Preheat Temp. (°F)	Extrusion Pressure (psi)		Extrusion Speed (in/min)	Processing Temp. (°F) ²	Processing Time (min)	Quench Type	Stretch (%) ³
				Initial	Final					
938	6061	R	960	1600	1500	10.5	985	80	Cold water	~1
940	6xSc	R	960	1700	1600	10.5	985	80	Cold water	~1
932	5456	R	930	3450	2800	2.1-3.6	480	80	Air cool	5
934	5xSc	R	930	3300	2600	3.2-3.5	480	80	Air cool	5
936	7xSc	R	800	2800	2500	3.5-3.8	875	60	Cold water	~1
941	6xSc	A	930	2800	2500	4.0	985	80	Cold water	~1
937	7xSc	A	800	3700	3100	1.5-2.5	875	60	Cold water	~1
935	5xSc	A	930	*	*	*	480	80	Air cool	5
933	5456	A	930	*	*	*	480	80	Air cool	5
939	6061	A	960	*	*	*	985	80	Cold water	~1

* data not available

¹ R = rectangular, A = A-frame section

² Temperature for solution heat treat (heat treatable alloys) or stabilization (non-heat treatable alloys)

³ Stretch for straightening (heat treatable alloys) or strain hardening (non-heat treatable alloys)

STAGE 2

HEAT TREATMENT AND AGING

The Al-Mg alloys, 5456 and 5xSc, were heat treated to a H116 temper (80 minutes at 480°F, 5% cold work). This temper was developed to increase the resistance to corrosion and stress corrosion cracking in alloy 5456.

Testing was performed on the heat-treatable alloys, 6061, 6xSc and 7xSc to select aging times and temperatures for T6 and T7 tempers. Artificial aging behavior for the A-frame extrusions is shown in figures 8 and 9. The Sc containing variant (6xSc) had a higher hardness in the naturally aged temper (time 0 in figure 8) than the conventional 6061 alloy. Hardness decreased during initial stages of artificial aging at 320°F and 350°F for the 6xSc alloy. This type of aging response (reversion) occurs as the fine precipitates that form during aging at room temperature become unstable and dissolve. Reversion was not observed in conventional 6061 specimens. On further aging (figure 8) hardness increased in both alloys, reaching a peak (defined as the T6 temper) after 16h at 350°F for 6061 and after 24h at 350°F for 6xSc. Although the Sc-addition increased strength in the naturally aged condition, it suppresses the artificial aging response and limits the peak hardness (figure 8). This may result from an interaction between Sc and Si that decreases the solubility of Si in Al (1).

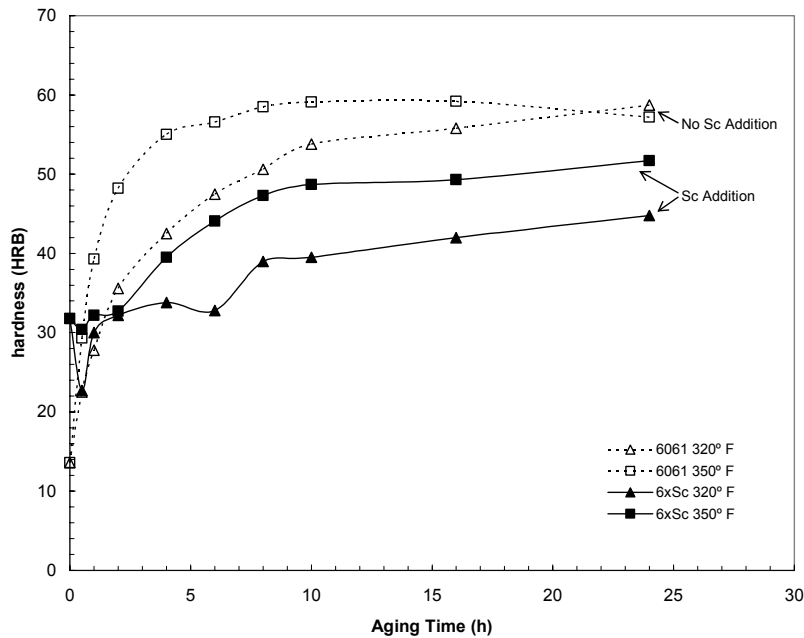


FIGURE 8 Hardness as a Function of Aging at 320°F and 350°F for 6061 “A-frame” Extrusions with and without the Sc Addition

Aging curves were also developed for 6061 and 6xSc rectangular bar extrusion. As observed in the “A-frame” extrusions the scandium addition suppresses the aging response and decreases the peak hardness in this alloy. The 6xSc alloy reaches a peak hardness between 30-80 hours.

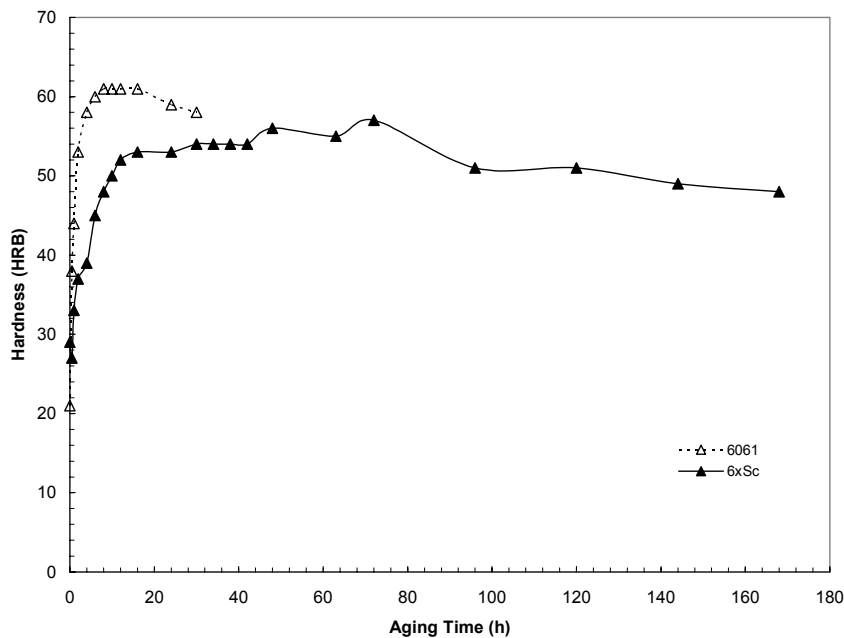


FIGURE 9 Hardness as a function of aging at 350°F for 6061 extruded bar with and without the Sc Addition

The aging response for the Al-Zn-Mg-Zr-Sc alloy, 7xSc is shown in Figure 10. The hardness decreases initially on aging for 0.5 hour at 250°F as the naturally aged microstructure reverts. This behavior is commonly observed in Al-Zn-Mg alloys (2) as the fine GP zones formed during aging at room temperature revert above some critical temperature (typically >100°C). After the reversion, the hardness increases, reaching a peak strength after 30 hours at 250°F. This aging response occurs as the η' -phase (MgZn_2) strengthening phase precipitates nucleate and grow.

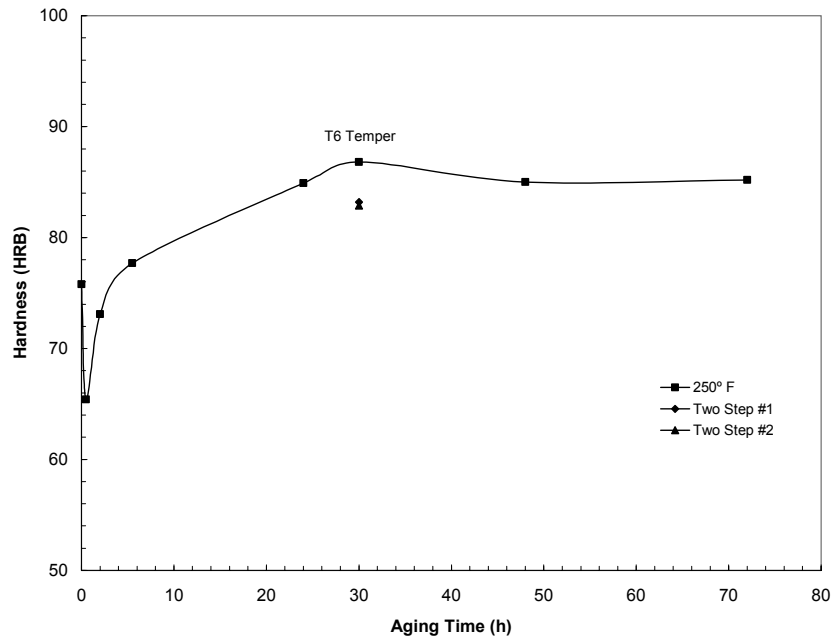


FIGURE 10 Hardness as a function of aging at 250°F for 7xSc “A-frame” extrusions

Testing was also performed to determine the aging conditions for the rectangular extrusions. The aging response for 7xSc rectangular extrusions was evaluated at 200°F, 250°F, 275°F, 300°F, and 325°F (figure 11). As with the “A-frame

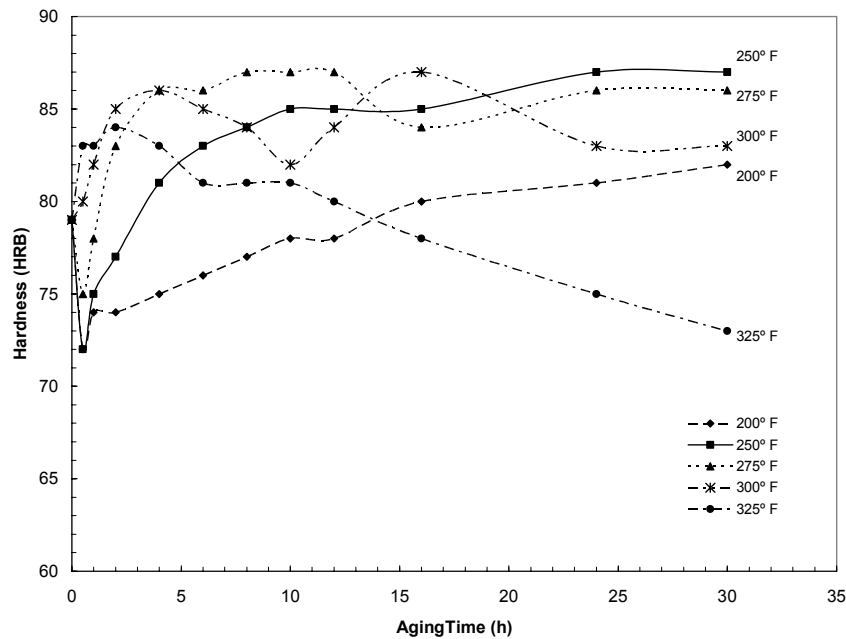


FIGURE 11 Hardness as a Function of Aging at 250°F for 7xSc “rectangular” Extrusion

extrusion,” hardness decreases on initial aging at 200°F, 250°F, and 275°F. The reversion observed at these three temperatures is followed by an increase in hardness. Peak hardness was reached after 8-12h at 275°F and after 24-30h at 250°F, hardness was still raising after 30h a 200°F. A reversion was not observed on aging at 300 and 325°F. Although lower aging temperatures result in a more uniform distribution of strengthening precipitates and higher strengths, commercial practice dictates that aging times be held at a minimum. As a result of this constraint, two step aging schedules (low temperature followed by higher temperature) are typically used for 7XXX alloys. This process uses

a low aging temperature to nucleate a uniform distribution of fine precipitates, followed by aging at a higher aging temperature which coarsens them. Several two-step combinations were evaluated for alloy 7xSc (figure 12). 250°F for 8 hours followed by 300°F for 3 hours was selected as the two step T6 heat treatment. A slightly overaged T7 type heat treatment was defined in addition to the T6 temper. The over-aged condition T7 temper was defined as, 250°F for 10 hours followed by 325°F for 9 hours.

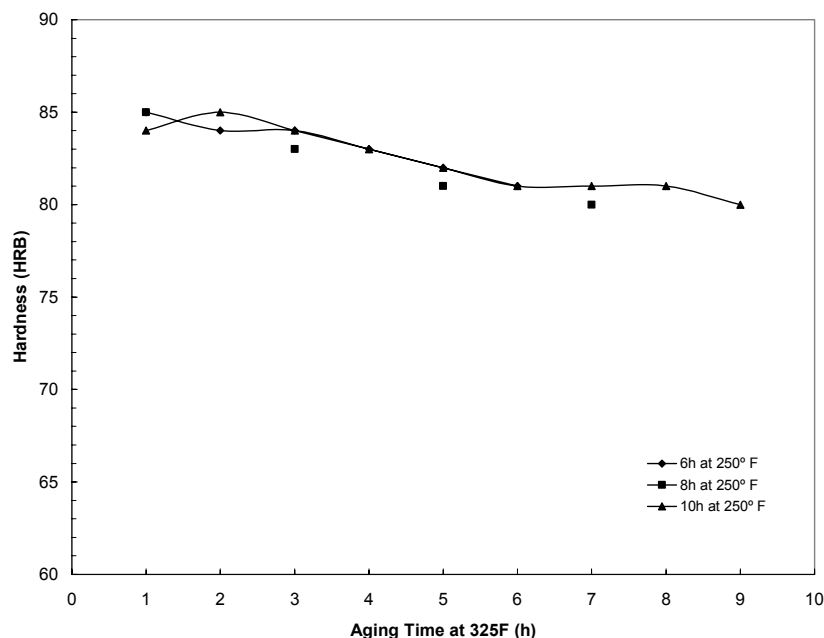


FIGURE 12 Hardness as a function of aging at 325°F for 7xSc “rectangular” extrusions

MICROSTRUCTURE

Microstructures of the rectangular extrusions (Figures 13-17) were examined perpendicular to the extrusion direction (LT-ST face) and parallel to the extrusion direction (L-ST face). The scandium containing 7xSc alloy has an unrecrystallized microstructure with pancaked shaped grains elongated in the direction of extrusion (figure 13). The refined grain structure in this alloy will provide high strength and resistance to environmentally assisted cracking. Conventional Sc-free Al-Zn-Mg-Cu alloys such as 7075 typically have a coarse equiaxed grain structure.

The Al-Mg-Si alloys, 6061 and 6xSc, have recrystallized microstructures (figure 14 and 15). The high Si content in this alloy may reduce the ability of the scandium to inhibit recrystallization. The scandium addition is effective at reducing recrystallization in aluminum-magnesium alloys (figures 16 and 17). Conventional alloy 5456 has a recrystallized microstructure with equiaxed grains (figure 16). The Sc containing aluminum-magnesium alloy 5xSc has a refined unrecrystallized grain structure (figure 17). Unfortunately large Sc containing primary phase particles formed in this alloy. The presence of these phases may be detrimental to mechanical properties of the alloy.

Sections of the A-frame extrusion were polished and examined. The extrusions exhibit a change in grain flow where the sections recombined in the die (figure 18).

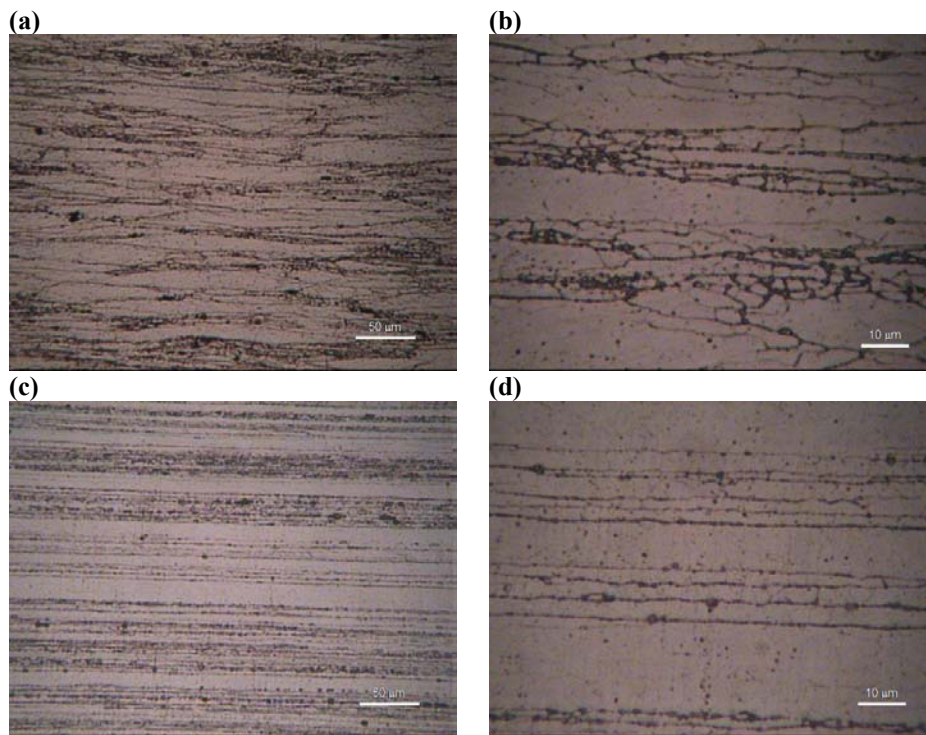


FIGURE 13 7xSc-T6 rectangular extrusion [Heat #936] (a) LT-ST 100x, (b) LT-ST 400x, (c) L-ST 100x and (d) L-ST 400x

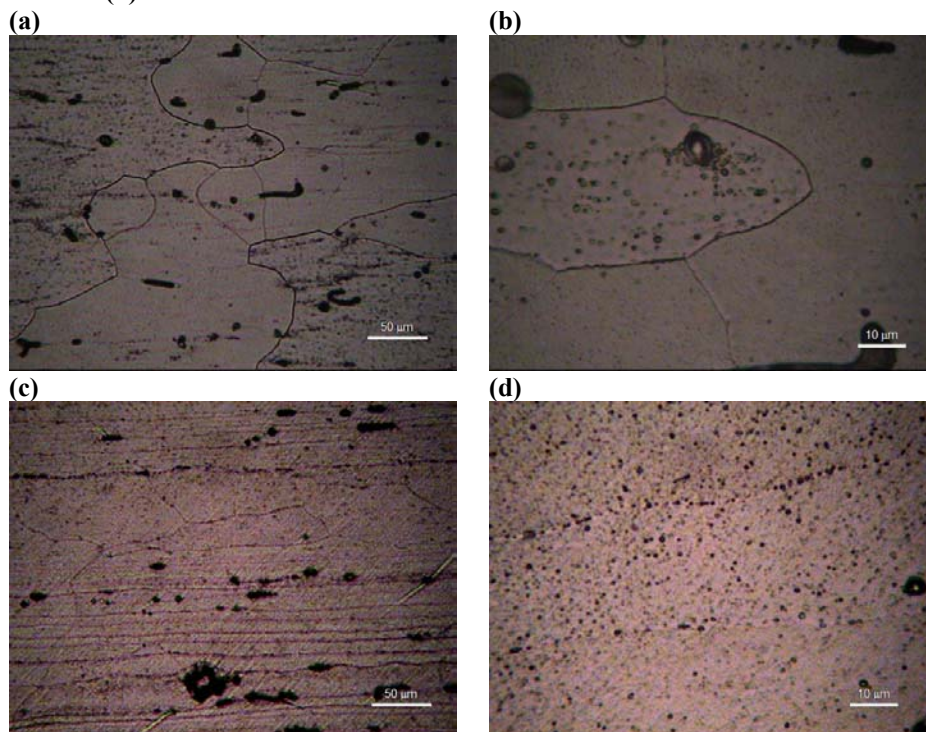


FIGURE 14 6061-T6 rectangular extrusion [heat #938] (a) LT-ST 100x, (b) LT-ST 400x, (c) L-ST 100x and (d) L-ST 400x

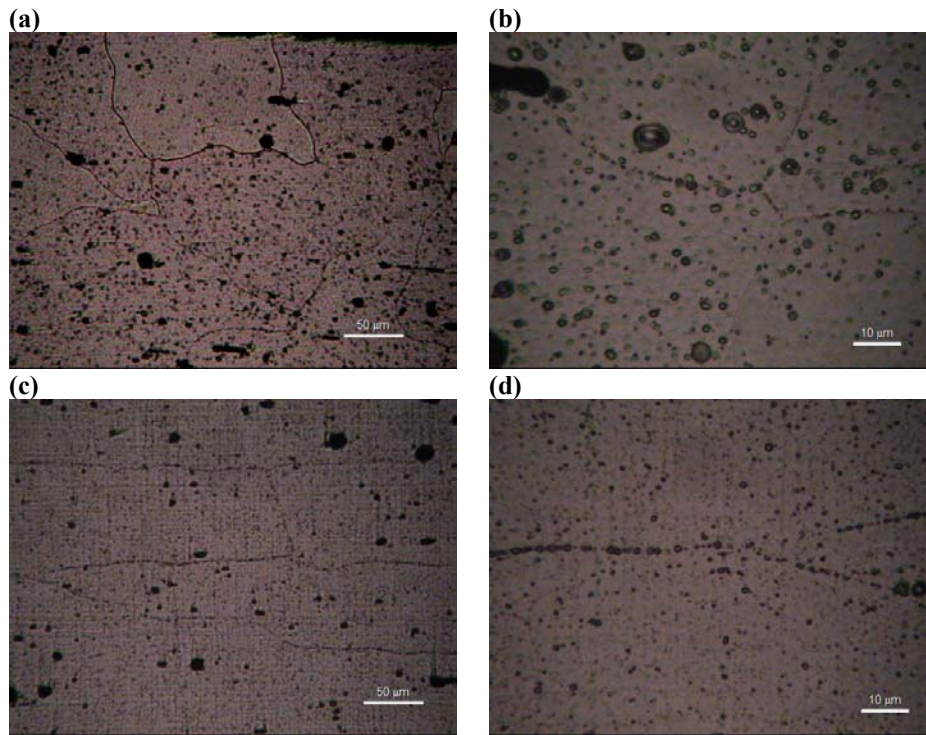


FIGURE 15 6xSc-T6 rectangular extrusion [Heat #940](a) LT-ST 100x, (b) LT-ST 400x, (c)L-ST 100x and (d) L-ST 400x

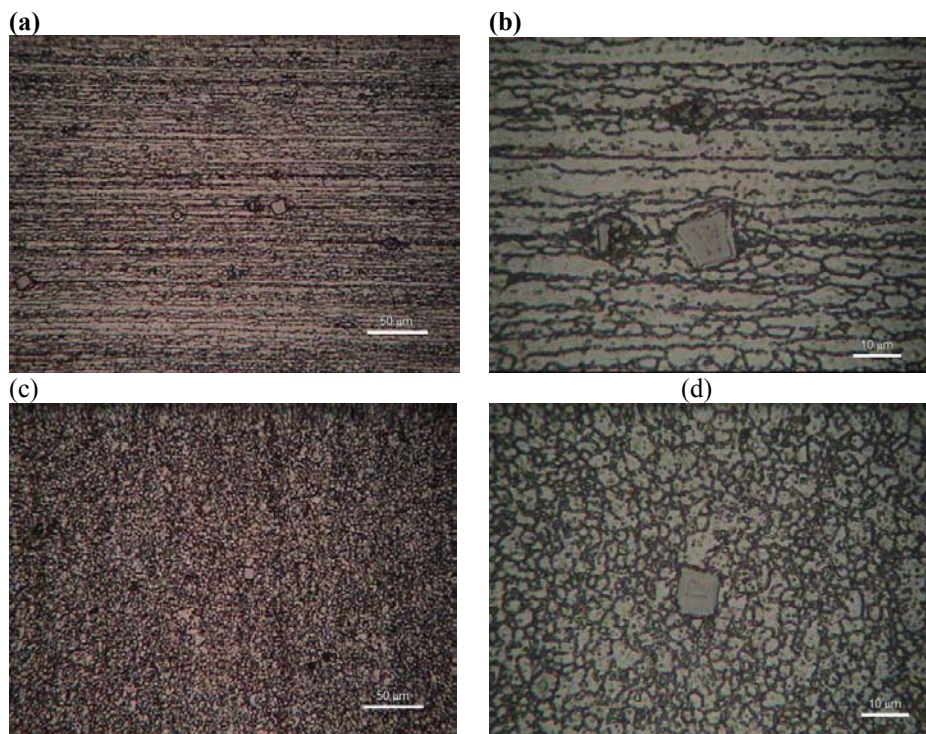


FIGURE 16 5xSc-H116 rectangular extrusion [Heat #934] (a) LT-ST 100x, (b) LT-ST 400x, (c) L-ST 100x and (d) L-ST 400x

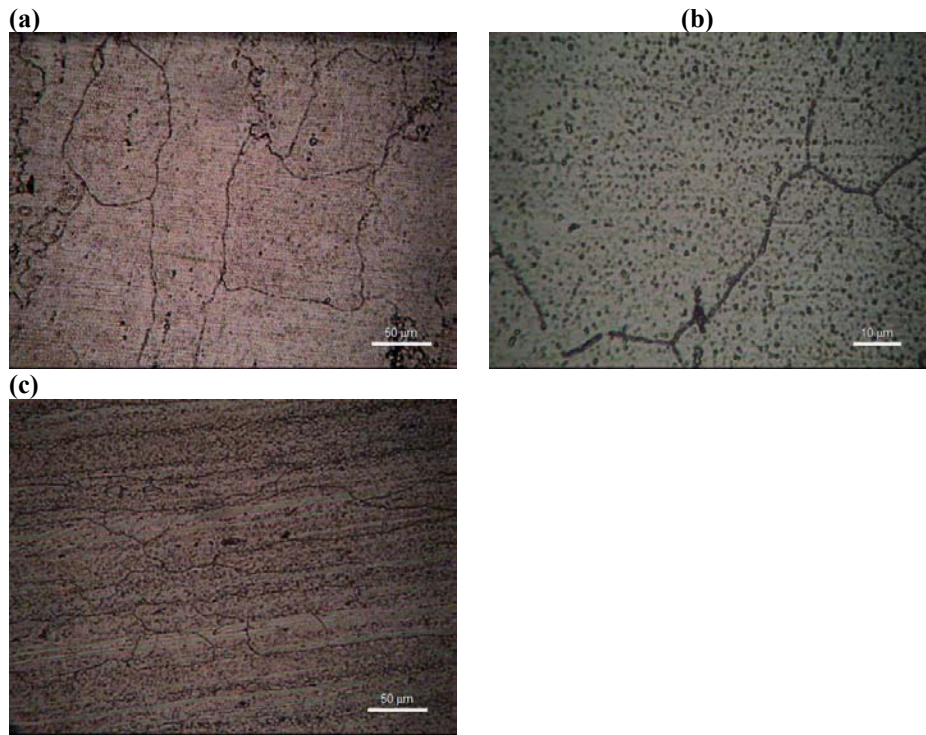


FIGURE 17 Alloy 5456-H116 rectangular extrusion [Heat #932] (a) LT-ST 100x, (b) LT-ST 400x, and (c) L-ST 100x

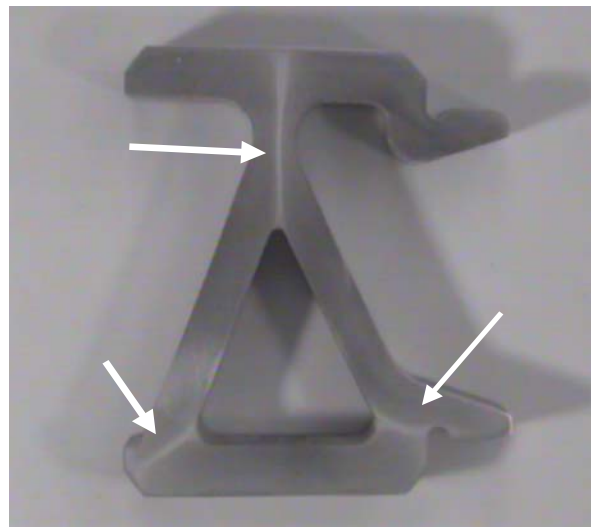


FIGURE 18 Alloy 7xSc Frame extrusion (#937) showing areas of recombination

MECHANICAL TESTING

Mechanical Properties were measured in accordance with ASTM E8 (3) using dog bone specimens machined from each of the three legs (Figure 19) of the A-frame section. Load during tensile testing was parallel to extrusion direction. The heat treatable alloys were solution heat-treated and aged to the T6 temper (Table 3). Specimens from section B of the extrusions had the highest strengths, although in most cases this differential was quite small. The highest yield strength was observed in the scandium containing 7xSc alloy. The addition of scandium to the Al-Mg-Si alloy 6061 decreased strength. Both the scandium containing and conventional Al-Mg alloys had much lower strengths than 7xSc.

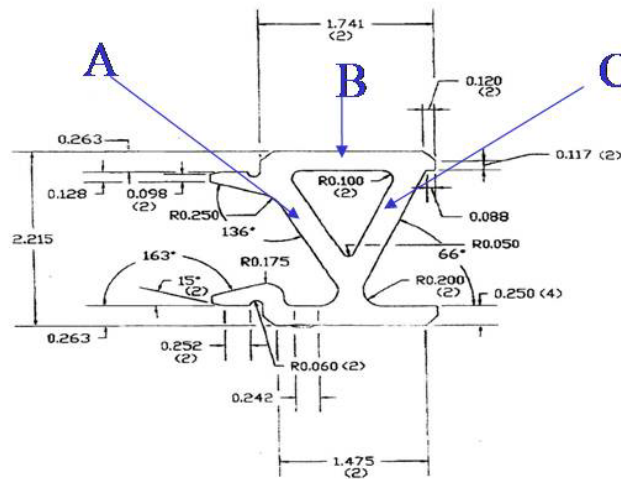


FIGURE 19 Location of tensile test specimens for A-frame extrusion

TABLE 3 Mechanical Properties of A-Frame Extrusion (See Table 1 for composition of alloys)

Alloy (Billet No.)	Temper	Section	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Hardness (HRB)
7xSc (937)	T6 30h at 250°F	A	68.2	72.0	18.1	78
		B	76.8	82.2	18.0	
		C	71.1	76.1	17.6	
6061 (939)	T6 16h at 350°F	A	43.1	46.1	17.1	67
		B	43.9	46.8	16.7	
		C	38.7	41.5	16.8	
6xSc (941)	T6 24h at 350°F	A	40.5	42.7	19.8	64
		B	40.6	42.5	21.3	
		C	40.1	42.8	20.7	
5456 (933)	H116	A	30.0	47.0	40.1	52
		B	33.2	50.1	35.9	
		C	29.9	48.9	38.5	
5xSc (935)	H116	A	33.3	53.8	38.2	52
		B	34.6	55.0	33.3	
		C	33.8	55.1	35.8	

Mechanical properties were also measured for the rectangular extrusions (Table 4). The heat-treatable alloys were aged to T6 and T7 tempers. The scandium containing alloy 7xSc had yield strengths of 86 ksi in the T6 temper and 76 ksi in the over-aged T7 temper. As with the “A-frame” specimens, the scandium addition decreased the mechanical properties of 6061 in the T6 temper. The high Mg, scandium containing alloy 5xSc was stronger than conventional alloy 5456. This increase in strength can be attributed to the refined grain structure in combination with the higher Mg level in the alloy. Strength of the 7xSc alloy in both extruded forms is comparable to high strength “aerospace alloys (e.g. 7075).”

Thus, based on mechanical properties, alloy 7xSc is clearly superior to the other candidate and baseline alloys. Historically high strength 7XXX series alloys have not been used to fabricate rolling stock due to poor corrosion resistance and a lack of weldability. Characterization of corrosion resistance and weldability were performed as part of the program to determine if the high mechanical properties of this alloy could be applied to fabrication of high speed car bodies.

Table 4 Mechanical Properties of Rectangular Extrusions

Alloy (Billet No)	Temper	Tensile Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Hardness (HRB)
7xSc (936)	T4	60.8	81.4	23.7	77
	T6	86.1	93.5	17.7	84
	T7	76.4	83.5	19.3	80
6061 (938)	T4	24.1	41.1	48.3	22
	T6	48.7	52.9	20.6	60
6xSc (940)	T4	24.6	38.7	57.0	30
	T6	46.4	49.0	18.5	57
5456 (932)	H116	32.6	49.0	33.1	46
5xSc (934)	H116	40.3	59.3	24.3	46

WELDING

Friction Stir Welding (FSW), a solid-state, thermomechanical process utilizing a rotating tool, was used by the University of South Carolina (USC) to join rectangular extruded sections of each alloy (Figure 20). The FSW tool (Figure 21) consists of a tapered, fluted, threaded cobalt alloy pin with a scrolled shoulder. All welds were made in one pass using rotational speeds of 320-720 rpm and linear velocities of 8-12 inches/minute. Downforce ranged from 7000-14,500 lbs, depending on alloy. Weld parameters were optimized for each alloy and verified via bend testing prior to welding a deliverable assembly. Alloy 7xSc was welded in the T7 temper and the 6061 alloys in T6.

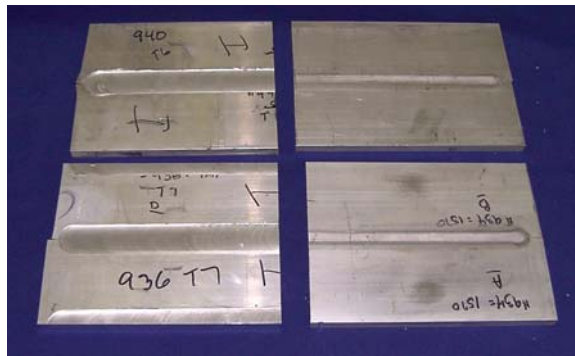


FIGURE 20 FSW assemblies – top surfaces on left, bottom surfaces on right

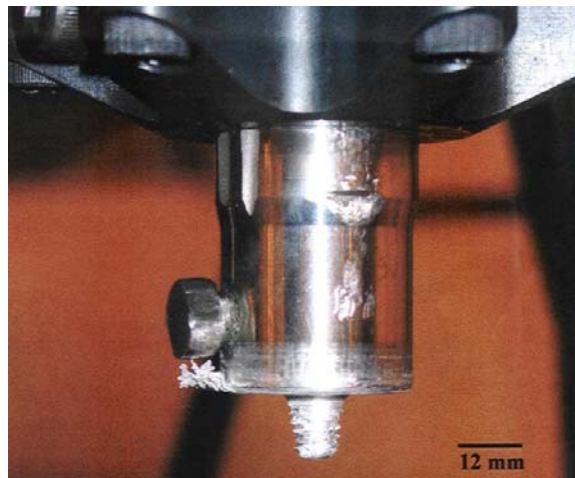


FIGURE 21 Friction stir welding tool

The microstructure of FSW (figure 22) is characterized by an extremely fine grain structure in the immediate vicinity of the welding tool. This “weld nugget” is very well defined and approximates the shape of the rotating tool with a bottom radius and a larger diameter crown that corresponds to shoulder penetration. Material in this region has undergone substantial deformation and the grains are much smaller than the base metal. Outside of the nugget, there is a region of larger grain size where some deformation has occurred and grain orientation changes according to position (advancing or retreating side of weld) and distance from the axis of rotation. USC refers to this area as the thermo-mechanically affected zone (TMAZ). Beyond the TMAZ there is a region resembling the heat-affected zone (HAZ) typically seen with fusion welding processes. Microstructures in various regions of a 7xSc alloy FSW are shown in figure 22. Note the difference between advancing and retreating sides of the weld. The transition between nugget and TMAZ is very abrupt on the retreating edge but more gradual on the advancing side. Tensile test specimens were taken from the welded assemblies. The specimens were machined such that the direction of welding was transverse to the load axis and the weld nugget was centered in the gage section. Results of mechanical testing are shown in Table 5.

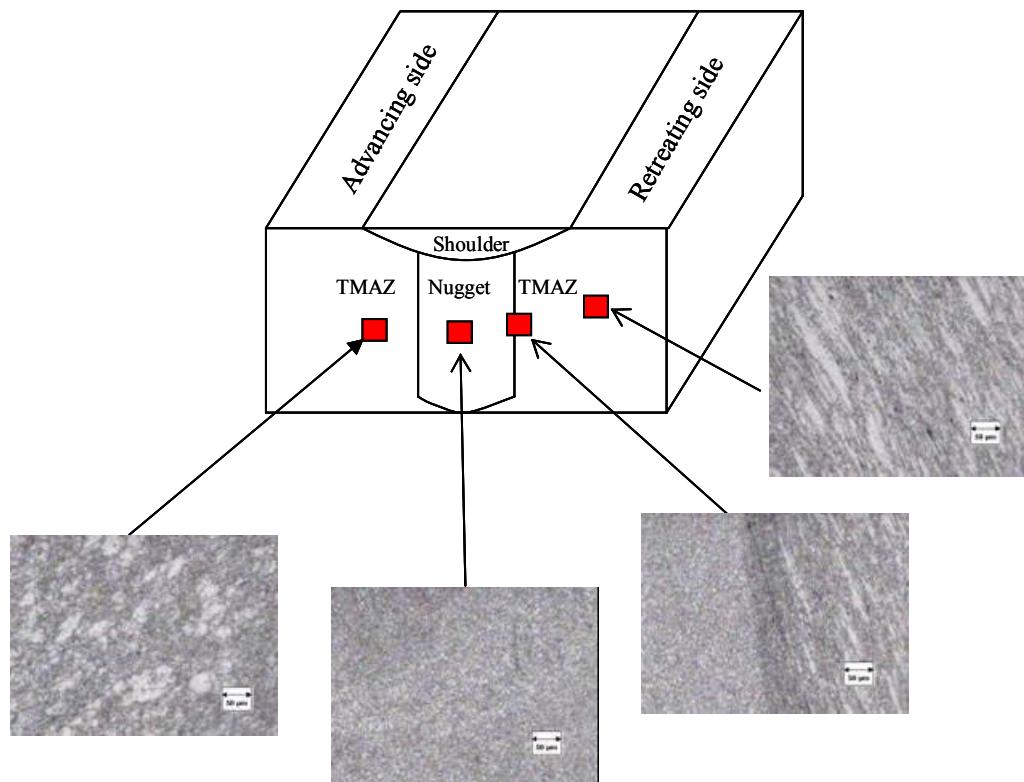


FIGURE 22 7xSc [Heat #936] friction stir weld

Table 5 Tensile Strength of Friction Stir Welds

No.	Alloy/Temper	Tensile Strength (ksi)	Joint Efficiency* (%)
936	7xSc T7	69.6	83.4
938	6061 T6	32.7	61.8
940	6xSc T6	36.7	74.9
932	5456 H116	27.0	55.1
934	5xSc H116	35.3	59.5

* Ratio of FSW to base alloy strength

Hardness measurements were made across the width of the welds (Figure 23). The non-age hardening alloys, 5456 and 5xSc, showed little change in hardness across the weldment. The age hardened alloys, 7xSc, 6061 and 6xSc, showed changes in hardness in the various regions of the weldment. High values are observed in the central nugget, followed by a decline reaching a minimum at approximately 0.2-0.4 inch from the center. 7xSc exhibits a secondary decrease in

hardness at about 0.75 inches from the center, believed to be the nugget / TMAZ transition. Moving through the TMAZ and HAZ transitions, hardness increases reaching a maximum values in the base metal region, at approximately 1.0-1.2 inches from the weld centerline. Hardness values for 7xSc were higher than any other candidate or baseline alloy at all points along the traverse.

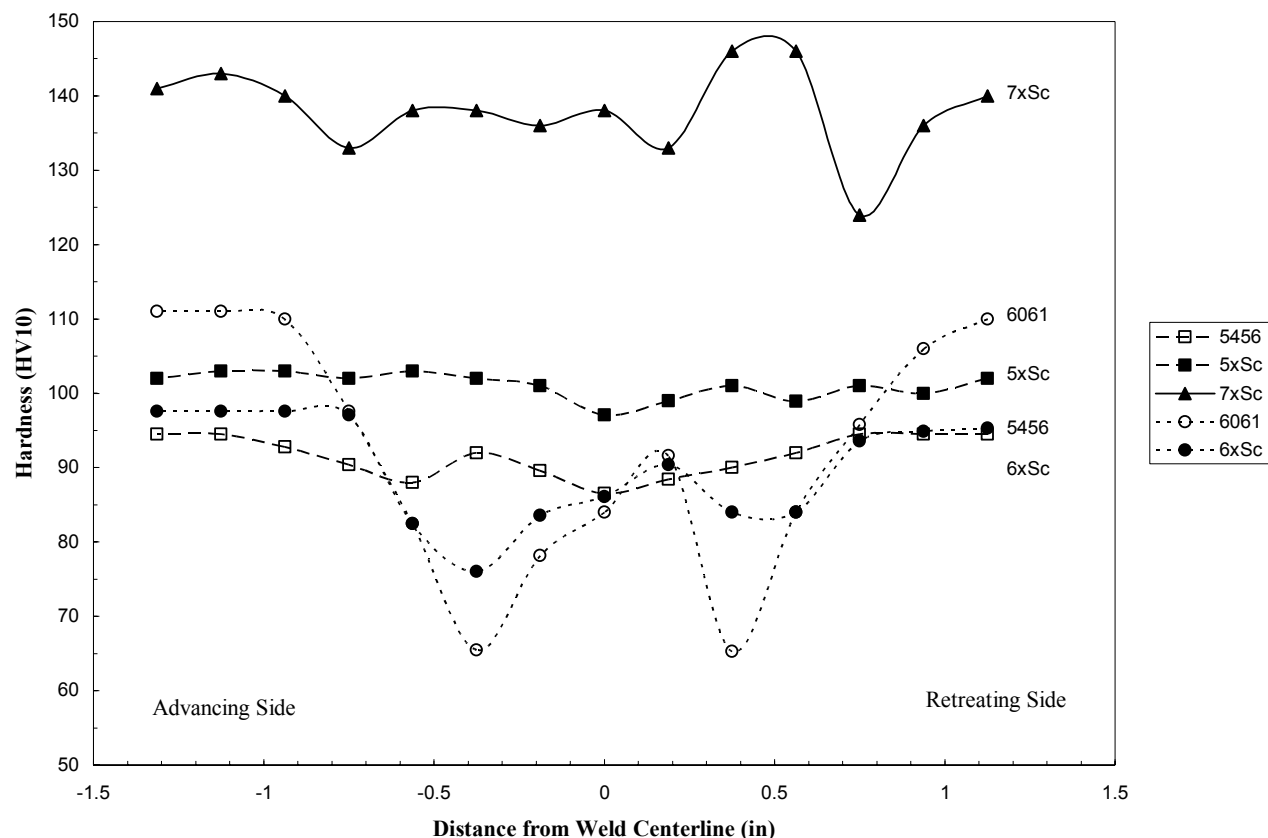


FIGURE 23 Hardness Traverse through FSW in the candidate and baseline alloys (Vickers Hardness)

Corrosion Testing

Susceptibility to corrosion was evaluated for the baseline and candidate alloys. Long-term exposure under constant immersion in an aqueous 3.5% NaCl solution was performed to evaluate corrosion rates (Table 6). Test coupons were prepared for immersion testing in accordance with ASTM G 31 (4). Three (3) coupons were sectioned from the rectangular extrusions for each alloy and exposed for an immersion period of 90 days. Visual observations throughout the test revealed no evidence of pitting type corrosion on any of the samples. Low corrosion rates were observed for both the candidate and baseline alloys. Variation in weight loss between the 3 coupons tested for each alloy was greater than differences between the alloys. Thus, corrosion due to exposure to saline environments does not appear to be a critical factor in alloy selection.

TABLE 6 Results of General Corrosion Testing After 90-Day Exposure

Alloy/Temper	Starting Wt. (g)	Final Wt. (g)	Corrosion Rate (g/m ² •yr)
5456 H116	6.7786	6.7782	-0.94
	6.7555	6.7553	-0.47
	6.7355	6.7348	-1.64
5xSc H116	6.7528	6.7522	-1.41
	6.7588	6.7581	-1.64
	6.7560	6.7551	-2.11
6061 T6	6.8517	6.8510	-1.64
	6.8623	6.8619	-0.94
	6.7971	6.7968	-0.70
6xSc T6	6.8462	6.8460	-0.47
	6.7732	6.7728	-0.94
	6.8817	6.8815	-0.47
7xSc T6	7.0334	7.0325	-2.11
	7.0364	7.0357	-1.64
	7.0656	7.0646	-2.35
7xSc T7	7.0624	7.0614	-2.35
	7.0632	7.0623	-2.11
	7.0367	7.0363	-0.94

Testing was also conducted to ascertain susceptibility of the aluminum-magnesium alloys to intergranular corrosion. These alloys were subjected to a 24-hour immersion in nitric acid [NAMLT test, ASTM G67 (5)]. Alloys that are susceptible to this type of corrosion will form a continuous network of β Al-Mg precipitates along the grain boundaries. These precipitates will be preferentially attacked by the acid; causing them to drop out of the alloy. This results in a relatively large mass loss. Alloys resistant to intergranular corrosion will lose only about 1-15 mg/cm² during this the NAMLT test. Susceptible alloys will lose 25-75 mg/cm². This testing revealed (Table 7) that 5456 is resistant to intergranular corrosion but that the Sc-containing alloy is highly susceptible, with a mass loss almost 18 times that of the conventional alloy. It should be noted that the thermal stabilization and strain hardening parameters for 5xSc are a replication of the H116 conditions for 5456 and were not optimized for the scandium-containing alloy. These conditions were used as a first approximation and it may be possible to develop a temper that prevents the intergranular attack observed with this alloy.

TABLE 7 Results of NAMLT Corrosion Testing

Alloy/ Temper	Avg. mass loss / Area (mg / cm ²)
5456 H116	4
5xSc H116	71

Stress Corrosion Cracking

Direct tension test samples were machined from rectangular extrusion to evaluate the resistance of 7xSc to stress corrosion cracking (SCC) in accordance with ASTM G44 (6), G47(7) and G49 (8). After machining, the specimens were aged to the T6 and T7 temper. One specimen from each temper was stressed to 0, 25, 50 and 75% of the yield strength and exposed for 40 days under alternate immersion (10 minutes in solution, 50 minutes out of solution) in an aqueous 3.5% NaCl solution. All samples were examined under 10x magnification twice each day during the test. No cracks or other failures were detected for 7xSc in either the T6 or T7 temper during the test period.

STAGE 3

ALLOY DOWN SELECTION

Alloy 7xSc was selected based on its high strength, good weldability, resistance to SCC, resistance to corrosion and good formability.

Fabricability The candidate and baseline alloys were successfully extruded in to bar stock using a convention die and into the “A-frame” using a porthole die. The Al-Mg-Si alloys, 6061 and 6xSc (soft alloys), required lower extrusion pressure and were extruded faster than 5456, 5xSc or 7xSc (“hard alloys”). Further evaluations of processing parameters should be carried out to determine if Sc containing “hard alloys” can be extruded faster without adversely affecting the grain structure since the rate of extrusion is a key factor in determining the cost of an alloy.

Mechanical Properties The aluminum-scandium alloy 7xSc has tensile yield strengths of over 70 ksi in “A-frame” and bar extrusions. These strengths are comparable with non-weldable high-strength aerospace alloys such as 7075. Alloy 7xSc is much stronger than other weldable alloys currently used to fabricate car body shells for high speed rail cars, with a yield strength that is 60% greater than 6061 and more than double that of 5456. Designers could use this increased strength to reduce weight by decreasing gauge of the side wall panels or to build a more impact resistant structure. Adding scandium to the Al-Mg-Si alloy 6061 did not improve mechanical properties. The scandium containing 5xSc alloy has a higher yield strength than 5456, but the large primary Sc phase particles may be detrimental to toughness and fatigue resistance.

Weldability The candidate and baseline alloys were successfully joined using the friction stir welding process. Hardness values measured in the weld region are close to those in the base metal for the 7xSc, 5456 and 5xSc. Both the 6061 and 6xSc weld regions were softer than the base metal. Although the scandium addition had no apparent effect weldability using the friction stir welding process, work by Kramer et al (9) and Tack et.al. (10, 11) showed that Sc additions decrease the susceptibility to hot cracking for fusion welded 6061. Thus, the scandium addition may be important for rail structures joined using conventional fusion welding processes.

Corrosion Resistance Candidate and baseline alloys showed a low corrosion rates when exposed for 90 days under constant immersion in a 3.5%NaCl solution. The Al-Mg-Sc 5xSc alloy was resistant to “general corrosion” but was highly susceptible to attack along sensitized grain boundaries. A temper development effort would be required to reduce or eliminate this susceptibility before using this alloy to fabricate rolling stock. No susceptibility to stress corrosion cracking was observed in the longitudinal direction for the high strength 7xSc alloy in either the T6 or T7 tempers.

PRELIMINARY CAR BODY DESIGN

Our ability to review current high speed passenger car body shells was limited due to proprietary nature of the designs. We were able to evaluate a number of advanced designs from Hitachi (12, 13) and Fiat (14) found in the patent literature. In all cases we evaluated, the side and top of the car body are built by welding a number of stiffened or hollow extruded aluminum panels together (figure 24-26). The longitudinal welds in these designs are not heavily loaded in service but may create maintenance issues during the life of the car and could create a safety issue in a collision.

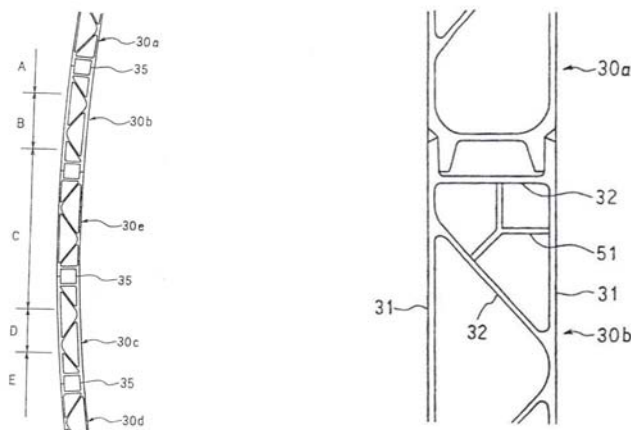


FIGURE 24 Design for passenger car shells (12)

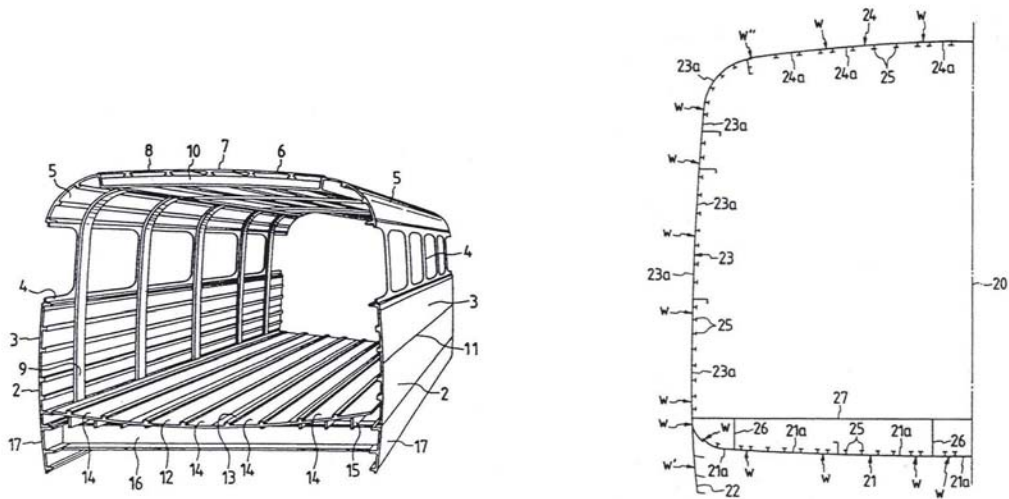


FIGURE 25 Design for passenger car shells (13)

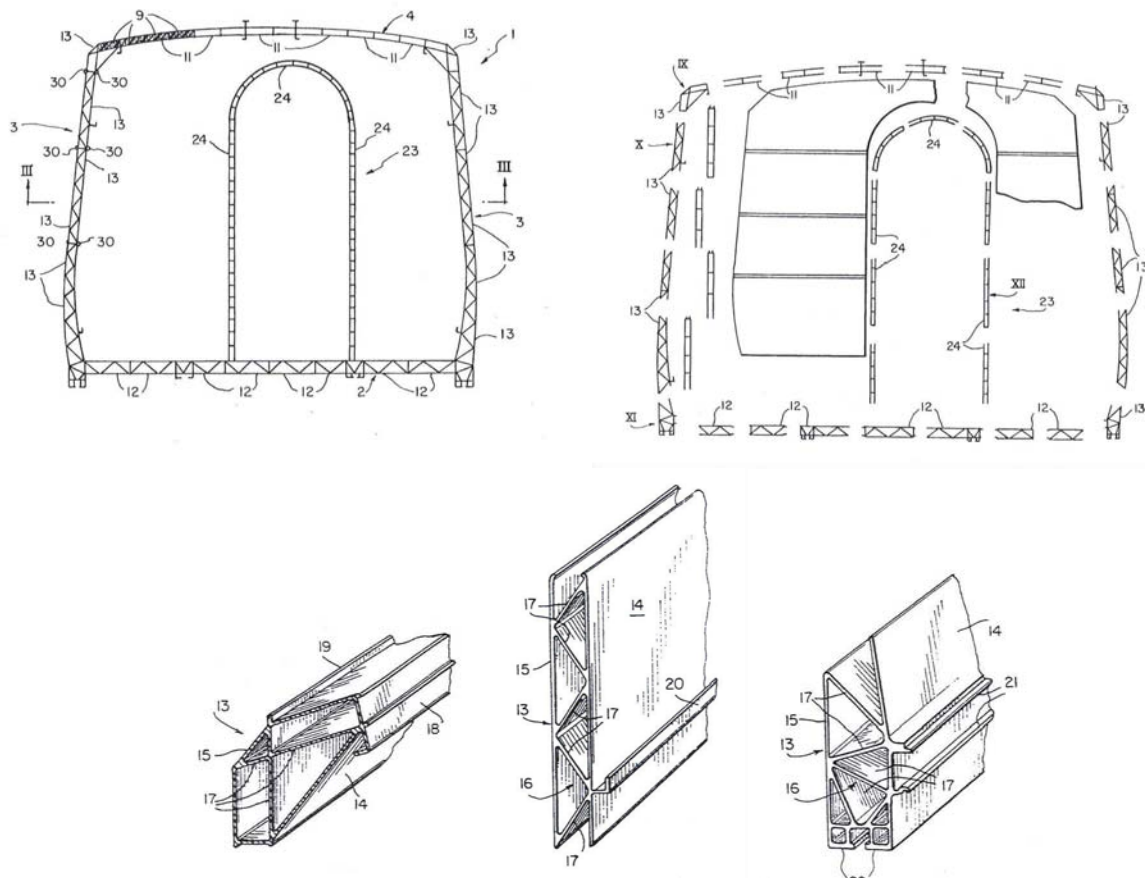


FIGURE 26 Design for passenger car shells (14)

A design approach developed by Surface Treatment Technologies that eliminates the longitudinal welds by forming monolithic side panels from integrally stiffened panels was evaluated. The panels for this design can be fabricated using a net shaped extrusion process. The initial step in this fabrication process involves the manufacture of large integrally stiffened pipe or U-shaped extrusions. The pipe extrusions are cut longitudinally and flattened to form large panels. Stiffened panels as large as 8 feet wide can be fabricated using this approach.

This approach was utilized by workers at the Martin Marietta Corporation under funding from the US Air Force to fabricate Ultra-High Strength Weldalite™ alloy barrel panels for cryogenic propellant tankage on space launch vehicle(15). These panels were fabricated from an integrally stiffened 35 foot long pipe extrusion with an internal diameter of 32.7 inches (figure 27a). The pipe was fabricated using a very large forging press to back extrude a pierced billet. After extruding the pipe was slit longitudinally and flattened to form an 8 foot wide panel (figure 27b).

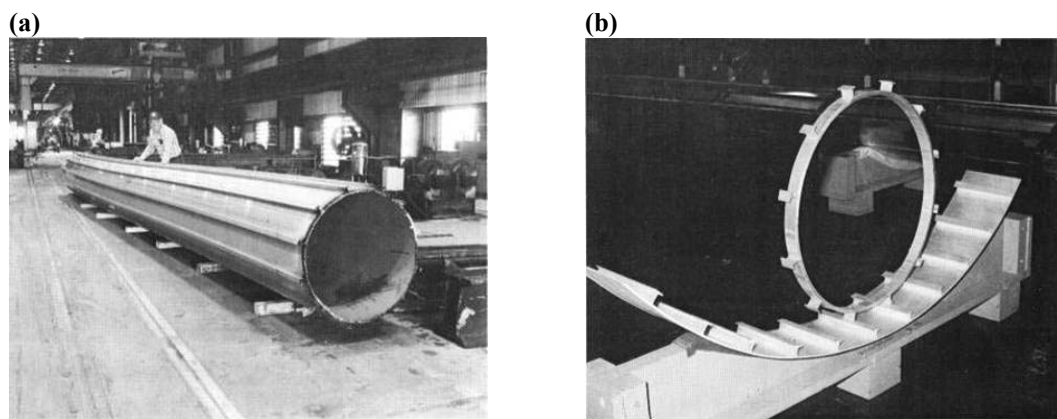


FIGURE 27 Full scale aluminum alloy integrally stiffened extrusion at Cameron Forge, Texas (Figure from Final Report, Development and Manufacture of Cryogenic Tank, National Launch System, Advanced Development Program #3106, Martin Marietta, 1993)

Boeing(16,17) evaluated a net shaped extrusion process as a means to produce low cost integrally stiffened fuselage panels. In their study they compared the cost and performance of fuselage panels fabricated using a conventional built up approach, an approach that utilized high speed machining to make stiffened panels from plate and an approach that used net shaped extruded panels. High strength alloy 7050-T74511 and 6013-T6511X integrally stiffened panels measuring 30 x 96 inches were procured (Figure 28). The high speed machining approach was selected for this application due to problems with dimensional stability and high raw material cost of large extrusions, but they concluded that “improvement in large extrusion technology—both to reduce the cost, and to improve the dimensional and mechanical properties--would likely benefit certain applications, and is worth doing.”



FIGURE 28 Aluminum alloy integrally stiffened extrusion (XXX)

Sample sections, an Al-Mg-Sc alloy and an Al-Li-Sc alloy, of integrally stiffened extrusions (figure 29) were obtained from a Russian aluminum company that currently produces integrally stiffened panels for aerospace components. The

cross section shown in Figure 29 was used to develop a preliminary car body shell design. This design (figure 30) is based on using a 3 foot diameter pipe extrusion to form integrally stiffened panels; one panel is used for each side wall and one panel is used for the top of the car.

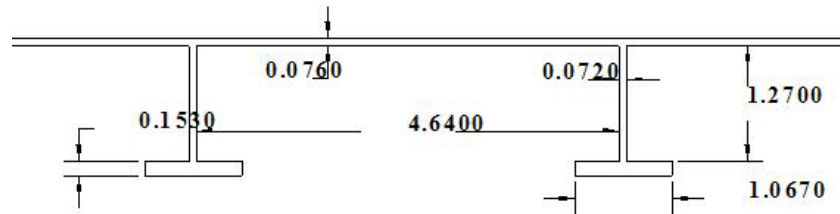


FIGURE 31 Net shaped integrally stiffened extrusion panel from Russian Aluminum Company

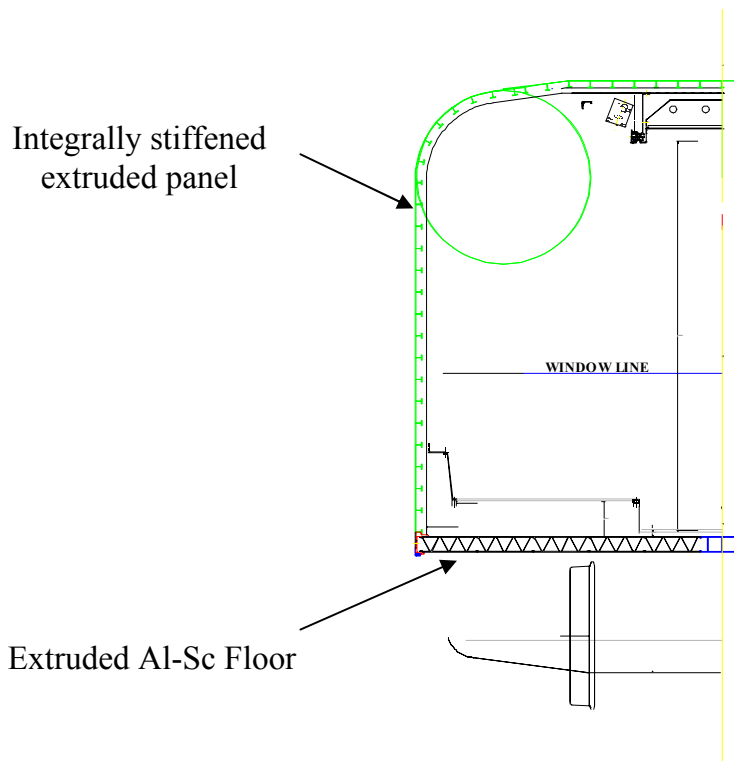


FIGURE 30 Preliminary designs for car body shell using ST2 net shaped extrusion concept.

ANALYSIS OF DESIGN CONCEPT

Finite element analysis was used to evaluate potential advantages of using integrally stiffened 7xSc alloy wide panel extrusions to build car body shells. The FEA model shows that replacing longitudinal welds improves resistance to side impact. A two “T” sidewall model with the following nominal dimensions was used for this modeling:

C/C spacing of T's	=	4 – 11/16”
Depth	=	1 – 7/16”
Width	=	1 – 1/16”
Inside Flange Thickness	=	1/8”
Web Thickness	=	1/16”
Outside Wall Thickness	=	1/16”

Load type – 20 psi lateral (sidewall) pressure on the outside wall of the section being analyzed. Two cases were analyzed employing ANSYS FEA models as follows:

1. **Convention design 6061 T6** case where there is a 1-inch weld region at the middle of the section. At the weld region, the modulus of elasticity was reduced to 5,500 ksi and the rest of the material was assumed to have 10,000 ksi of young's modulus. (The material being used is 6061-T6 aluminum)
2. **Integrally Stiffened Al-Sc Alloy** case where there is no weld and the material has a modulus of elasticity of 10,400ksi. This model simulates integrally stiffened Al-Sc alloy 7xSc extruded panels.

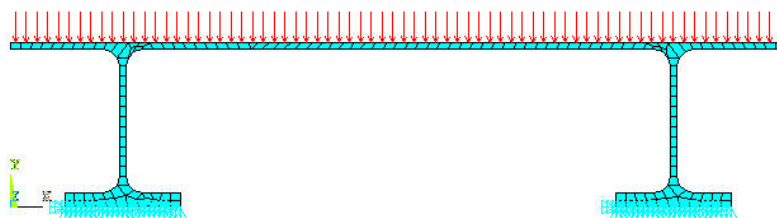


FIGURE 31 Geometry, boundary conditions and loading of the analysis.

Comparison of Deflection

The section with middle weld has a midspan deflection of 0.20 -inch as compared with that of the uniform section which has a midspan deflection of 0.15 -inch for the same loading.

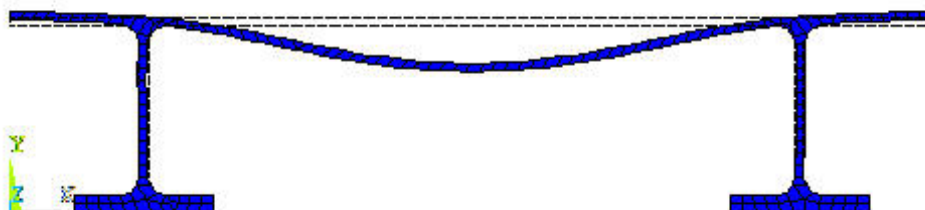


FIGURE 32 Deflected Shape of the 7xSc alloy extruded section with no Weld.

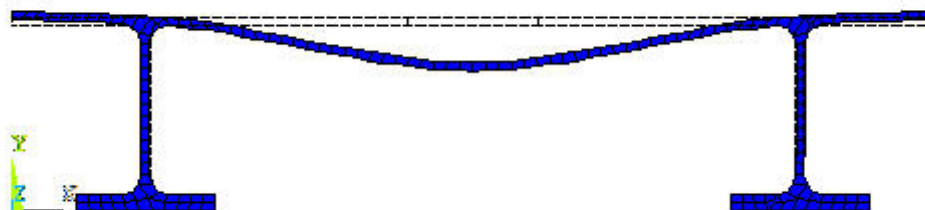


FIGURE 33 Deflected Shape of the 6061-T6 extruded Section with Middle Weld.

Comparison of Stress in the X-Direction (Sxx)

The analysis showed that loading the 7xSc extruded section results in a maximum compressive stress of 56 ksi and tensile stress of 46 ksi. Both are less than the yield strength (68.2 ksi) of the alloy. The section with the middle weld develops a maximum compressive stress of 59 ksi and tensile strength of 56 ksi which exceeds the yield strength (38.7 ksi) and ultimate tensile strength (41.5 ksi) of 6061. Thus, integrally stiffened 7xSc extrusions would clearly perform better than the welded 6061.

Comparison of Sx at the Midspan Region

The analysis also showed that the section without a weld develops tensile stress of between 24-36 ksi at the mid-region which is well within the yield strength of 7xSc (68.2 ksi). The 6061-T6 section with middle weld develops tensile stress of between 31-40 ksi. For the model we assumed that the strength of aluminum is reduced by 45% at the weld region (around 20 ksi for the 6061 in the weld region). Thus, the section with middle weldment would fail under the current loading condition. Again the model clearly indicates that the 7xSc integrally stiffened extruded section would perform better than the welded 6061-T6 section.

Comparison of Shear Stress :

Modeling showed that shear stresses in the welded 6061-T6 aluminum sections are higher than those in the integrally stiffened 7xSc alloy extrusion by nearly a factor of two (3100 vs. 1700 psi). It should also be noted that the base of the "T" sidewall section of the 6061-T6 aluminum with center weldment exhibits increased relative shear stress from the loading condition that does occur in the parallel case with 7xSc alloy.

SUMMARY AND CONCLUSIONS

Alloy Selection

Although aluminum alloys have been used extensively in the construction of passenger rolling stock, corrosion problems have limited the use of high strength aerospace type alloys. The key goals in this program were to determine if alloying with scandium increases the performance of the alloys currently used in the rail industry and to evaluate a scandium containing high strength alloy for rail applications. Two key issues related to scandium additions in aluminum alloys were addressed 1) the effect of scandium on strength of Al-Mg-Si alloy 6061 and 2) the effect of scandium on strength and corrosion resistance of Al-Mg alloys.

Previous work by Tack (10, 11) showed that Sc additions improve weldability of Al-Mg-Si alloy 6061 by decreasing susceptibility to hot cracking. Work in the Former Soviet Union (FSU) (1) showed that Scandium additions decrease solubility of Si in Al-Si-Sc alloys, which adversely affects age hardening. The present study showed that the Sc addition decreases strength in the T6 temper for alloy 6061 and does not refine grain size. In addition, the Sc addition did not improve properties of friction stir weldments. Thus, adding scandium to conventional wrought Al-Si-Mg alloys will not increase performance in high speed rail applications joined using the FSW process.

Conventional Al-Mg alloys, e.g. 5456, are not age hardenable. These alloys are strengthened by Mg atoms in solid solution, cold work and Hall Petch strengthening due to grain boundaries. Work in the FSU has focused on increasing strength in Al-Mg alloys by increasing Mg content and reducing grain size. The magnesium content in the scandium containing candidate alloy 5xSc is higher than that found in conventional Al-Mg alloys. The high scandium content in the alloy refined the grain size. This increase in Mg in combination with the refined grains resulted in an increase in mechanical properties. Unfortunately the H116 heat treatment used to reduce intergranular corrosion in 5456 did not work in the 5xSc alloy. Further development efforts would be required to establish a corrosion resistant temper for this alloy. When compared with alloy 7xSc, it appears that the modest gains in strength observed in this alloy would not warrant the cost premium associated with the scandium addition.

High strength aerospace alloys are not used to fabricate passenger rolling stock due to corrosion issues. The scandium containing alloy 7xSc has strengths higher than high strength aerospace alloys (Table 8) but it does not suffer from localized corrosion. The life cycle cost savings associated with using this increase in strength to reduce weight on rolling stock will be evaluated as part of ongoing interactions with car builders. This increased strength could also be used to make stronger safer car body shells.

Table 8: Mechanical Properties of Typical Aerospace and Marine Al Alloys

Alloy	Yield Strength (ksi)	Tensile Strength (ksi)	Strength	Corrosion Resistance	Weldability
5456 H116 (Al-Mg)	32	49	Low	Good	Good
6061 T6 (Al-Mg-Si)	49	53	High	Moderate	Moderate
7xSc T7(Al-Zn-Mg-Cu-Sc-Zr)	76	84	Very High	Good	Good
7075 T6 (Al-Zn-Mg-Cu)	67	76	Very High	Poor	Poor

Cost

The extrusion rate for aluminum is related to the complexity of shape and the extrudability of the selected alloy. In production the throughput for an extrusion press and subsequently the cost per of extruded product is related to extrusion rate. So called hard alloys, Al-Zn-Mg-(Cu) and Al-Mg, are extruded much slower than soft alloys, Al-Mg-Si (6061) thus are more expensive to process. Work is under way to reduce this cost premium by utilizing novel improvements in processing parameters.

At present, scandium containing alloys are produced as a premium product due to the relatively small volumes used in high performance sporting goods. Increases in production volumes required to meet newly created demands in the rail and marine industries will reduce cost. This increase in demand will also create a larger market for the Al-Sc master alloy, which will lead to more competition and lower costs. Further study is required to define absolute cost savings associated with the increase in performance of these alloys.

Design

Current high performance car body shells are designed to be fabricated by welding a number of long aluminum alloy extrusions together to form the walls. The design evaluated in this program uses large integrally stiffened panels for the side walls and roof of the car. Preliminary FEA analysis showed that removing the welds will improve side impact strength. At present very large integrally stiffened panels are not fabricated in the United States. A path has been located which utilizes an extrusion press that will come on line in late 2004. This 16,000 ton press, the largest indirect press in the world, has a 45" container and has been used to fabricate 40" wide integrally stiffened panels. Work will be required to develop procedures to produce large panels that meet dimensional stability required for fabrication of car bodies.

Utilizing the high strength scandium containing aluminum alloy in the novel ST2 design would result in a safer high performance high speed passenger rail car. ST2 plans to work with designers at a car builder to implement advanced alloys and novel design concepts into the next generation of passenger car rolling stock. As part of this program, a subscale car shell be fabricated and tested. In addition, a detailed cost analysis will be performed to show cost savings associated with reduction in manufacturing and operating costs.

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