

MSE 140B Report Group #3

**MATERIALS SELECTION FOR WEIGHT
REDUCTION OF SUSPENSION
CONTROL ARMS**

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Abstract

To remain competitive within the Baja SAE competition, a search for high-strength, low-density materials was essential. The control arms for the M25 off-road all-terrain vehicle (ATV) were evaluated in terms of strength and weight quantitatively, while considering material weldability and machinability for the final selection. The material selection was narrowed from AISI 4130 steel to 7005 Al through a screening process, which utilized Ashby plots based on several defined design requirements. Materials that passed the screening process were filtered further using a developed Figure of Merit equation in the ranking process. Alloy composition of the acquired 7005 stock was verified through XRF, and welded specimens were fabricated using AC TIG welding with ER5356 filler metal. An artificial aging treatment was applied to mitigate strength losses associated with welding. Optical microscopy, SEM, EDS, and Vickers hardness testing were used to characterize the effects of welding and heat treatment. Finite element analysis was performed to validate the redesigned control arm under representative competition loading conditions and identify critical failure locations. Results showed that heat treatment improved weld-region hardness and microstructure, while the redesigned 7005 control arm achieved a 63.4% weight reduction compared to the 4130 design and satisfied all geometric and performance requirements. These findings demonstrate the viability of 7005 as a lightweight alternative for Baja SAE suspension components.

Background



Figure 1. UCLA Baja M24 Control Arms.

Weight optimization is of vital importance to automotive racing performance. Material selection must consider a compromise of manufacturability, cost, weight, and strength for the best possible performance achievable in the Baja Society of Automotive Engineers (SAE) season.

The previous report had revealed that the control arms on UCLA's previous Baja car (M24) was made primarily of 4130 steel [1]. Steel tubing was welded together with wafers and tabs to form the fully realized component. The material selection and the quality of the weld allowed the control arm to provide enough strength to go through the rigorous load cases seen in competition such as high jumps or other cars rolling onto the wheels. However, the control arm came to be extremely hard to manufacture due to the hardness of the steel; having a Brinell hardness of 95 [2], and each weighed 3.15 lbs.

A general bill of materials for an upper control arm is visualized in Figure 2, where the upper control arm is composed of the frame, wafer, and tab. The frame contains bushings and is fastened to the chassis with nuts and bolts while the wafer is assembled with a spherical bearing, high misalignment bushings, and a retaining ring. Material selection and design is focused on the main components for this study due to time, complexity, and money.

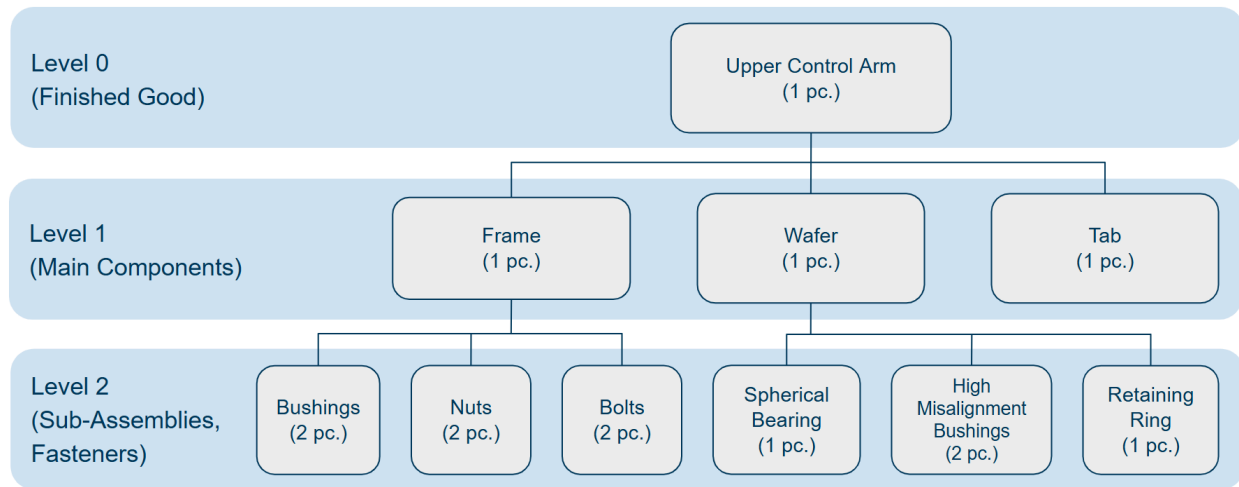


Figure 2. Bill of materials for an upper control arm.

For the Model 25 (M25), the control arms were to be reimaged and that started with the very material used for them. High strength to weight alloys immediately became suspect for viability, such as aluminum alloys. Main considerations for such low-density-high-strength alloys are tradeoffs in terms of weldability and stock material cost in comparison to steels.

A material will be labeled as unweldable due to hot cracking that occurs, which makes arc welding difficult. This issue is due to the effect of alloyed elements having low solidification temperatures and the solidification shrinkages occurring, inducing thermal stress within the weld. Another factor that affects an alloy's hot cracking is the coherence range. This describes the temperature range where dendrites begin to interlock with one another and the solidus temperature. Alloys with a larger coherence range have a greater chance of hot cracking occurring due to higher strains building between the connecting dendrites [3]. Stress builds at the grain boundaries and is further worsened with repeated passing until a crack forms, as seen in Figure 3 [4]. The aluminum series of 5XXX and 6XXX is seen as weldable due to not being as susceptible to hot cracking compared to other series, such as the 2XXX series. Some alloys are

added with certain elements to refine grain size and reduce sensitivity to hot cracking, such as adding Zr to 7005 [5].

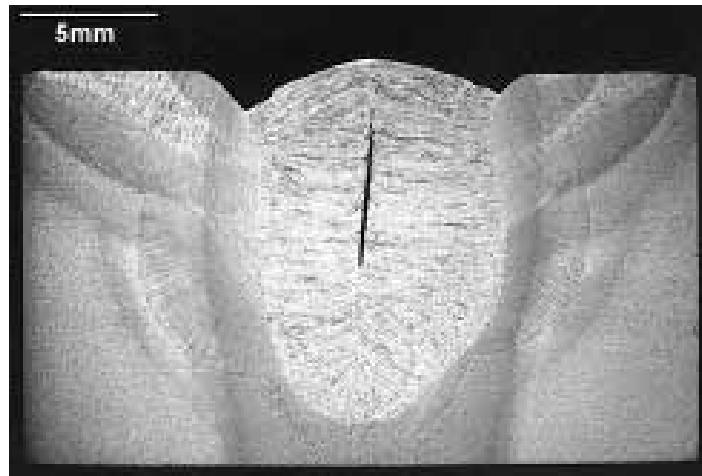


Figure 3. Hot Cracking Within a Weld [4].

When using weldable alloys, both the correct filler rod choice and protection against oxidation layers must be considered for alloys of any type of weldability. Filler alloy selection must be similar to the specific base material being welded, else the components of the filler rod negatively affect the coherence range [3]. Aluminum is incredibly susceptible to forming oxide layers. The oxides formed have a much higher melting point than pure aluminum, being around 2000°C versus 650°C. The oxide layers must be removed before welding, and attempts to melt them may burn holes through the base material [6]. Other general welding issues stem from high thermal conductivity and low melting points of materials, which increases susceptibility to being burnt through or leaving weld pools with heavy porosity [6]. Aluminum's extremely high thermal conductivity leaves its welded joints weaker than the base material, unlike in steels, as the welded joint is overaged and all work hardening becomes annealed with the high heat inputs required [7].

The heat treatment capabilities of an alloy may be able to offset both the base material's initial strength as well as poor welded joint strength. The 6XXX and 7XXX series of aluminum, for example, can make up for their lack of strength, in comparison to most steels, by utilizing precipitation hardening, which can strengthen both the base material and the heat-affected zone (HAZ) of the weld. For the maximum strength of an alloy to be achieved, it needs to undergo solution treatment, quenching, and finally ageing [8]. Solution treatment involves heating an alloy just under its melting temperature to allow for greater homogeneity of precipitates within it, forming a supersaturated solid solution. Quenching has the alloy rapidly cooled to room temperature, locking it in a metastable phase. Finally, the process ends with aging, which is where the alloy is heated to a temperature lower than in the solution treatment phase to initiate precipitation. Ideally, these precipitates are grown to a fine size to hit their peak hardness and yield. The precipitates inhibit the movement of dislocations and slip within the material matrix, improving the material strength. Overaging can occur when heating the

material further, causing coarsening of the precipitates and instead decreasing the strength, as seen in Figure 4. Quenched 6061, for example, forms Mg-Si clusters which can then precipitate into needle-shaped β phases [9]. Aging can be done at room temperature or at elevated temperatures; natural versus artificial aging. After 3 months of natural ageing, the heat-affected zone of a 7005 can recover 100% of its original strength, showing an example of the recovery of strength being possible in aluminum welded joints to make up for the initial loss in strength [5].

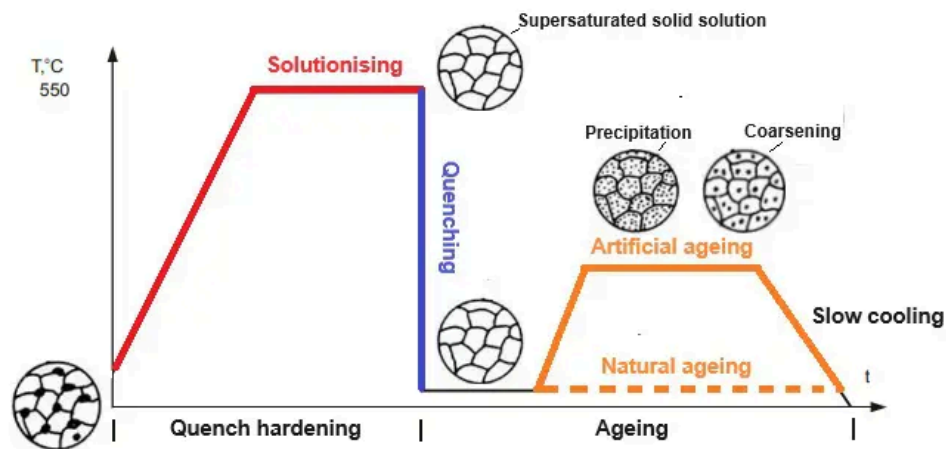


Figure 4. Steps to Age Harden Aluminum [8].

Another consideration for material selection and the applications of the control arms concerns the general lifetime of the product and ease of replaceability. The steel control arms were far stronger and harder, able to withstand greater loads. They did not require being swapped with spares often or repairing certain segments with new material. The material is far easier to weld and lacks any signs of burning through the material. On the other hand, softer alloys have a greater ease of manufacturing. Cutting pipes or running computer numerical control (CNC) operations have far less risk of breaking any tools, while running far quicker. The availability of stock, however, may also limit the potential for large supplies of spare parts to be as accessible economically, compared to 4130.

Design Requirements

For the upper control arm to operate successfully in high-impact off-road conditions, it must meet several design requirements. Firstly, a major consideration in the design of the control arm is how it integrates with the other components on the car. Namely, it must not interfere with other suspension or steering components, such as the shock and tie rod, which are shown in Figure 5 [10]. In addition, since one of the main functions of the control arm is to connect the frame of the car (the chassis) to the wheel assembly, it must feature two chassis mounting points as well as one knuckle (or steering upright) connection point [11].

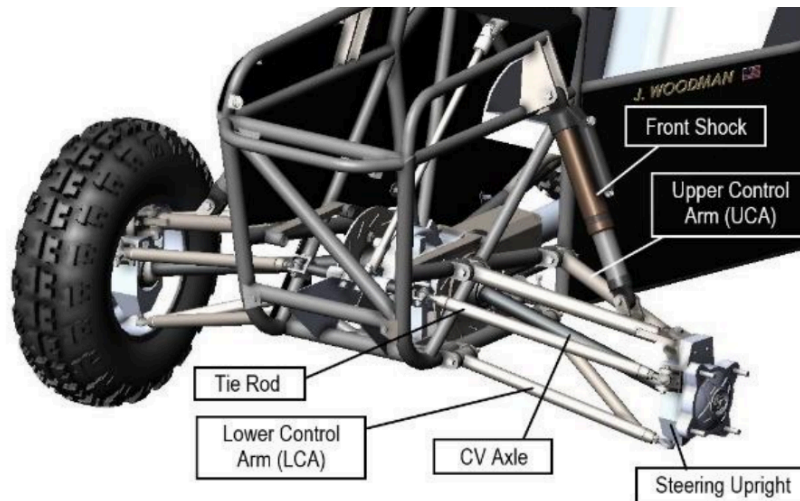


Figure 5. Diagram of front suspension components. [10]

Mechanically, the control arm must be able to withstand an extreme load case, which we defined to be a 2g-force event focused on a single wheel, representing a conservative worst-case scenario impact that can occur during a collision with an obstacle or when aggressively cornering. The value 2g was chosen as values between 1.5-3g are common assumptions used in the design and analysis of suspension components [12]. Given that the combined weight of the car and the driver amount to approximately 600 lb, the minimum load the arm must withstand is calculated as the g-force multiplied by the weight, resulting in 1200 lbf. This load value is applied in Finite Element Analysis (FEA) in the Discussion section, with a target Factor of Safety over 1 for material optimization. From Finite Element Analysis, the maximum von Mises stress (304.47 MPa) is obtained, which defines the minimum yield strength the new material must be.

The control arm is to be manufactured using existing fabrication techniques within the UCLA Baja SAE team, which includes the use of Tungsten Inert Gas (TIG) welding and AWS 5356 filler rod. As such, the new selected material also must be easier to machine than last year's control arm, previously made of 4130. Machinability can be closely correlated with hardness as a higher hardness increases cutting forces, tool wear, and machining time. Accordingly, Brinell hardness (HB) can be used as a quantitative metric for machinability, with lower values preferred relative to the 4130 baseline. This parameter is evaluated later in the ranking section.

Considering how weight minimization directly benefits vehicle performance, the new control arm design must be lighter than the previous control arm design overall [13]. By the same reasoning, a less dense material than 4130 should be used (less than 7.85 g/cm^3) [2].

Lastly, in a suspension system, the upper control arm (UCA) works in conjunction with the lower control arm (LCA) to maintain alignment. The UCA ensures steering stability while the LCA handles the majority of the vehicle's weight and impact loads [14]. Hence, the shock is typically mounted on the LCA but can be mounted on either the UCA or LCA, making this a free

variable to be considered in the new design. Other free variables include choice of material and cost. The aforementioned design requirements are summarized in Table I where the main objectives, derived from these constraints, are also defined.

Table I. Design Requirements for the Upper Control Arm.

Function	Upper Control Arm
Constraints	Geometric: 1. No interferences with other components on the car 2. Must feature two chassis mounting points 3. Must feature one knuckle connection point Mechanical: 4. Must withstand 1200 lbf with a Factor of Safety > 1 Manufacturing: 5. Weldable via Tungsten Inert Gas (TIG) Welding 6. AWS 5356 filler rod compatibility 7. Good machinability relative to 4130 baseline Material: 8. Density, $\rho \leq 7.85 \text{ g/cm}^3$ 9. Yield strength, $\sigma_y \geq 304.47 \text{ MPa}$ 10. Overall mass < 3.15 lb
Main Objectives	1. Minimize weight 2. Maximize yield strength 3. Ensure material compatibility with team's current welding processes 4. Maintain good machinability
Free Variables	1. Choice of material 2. Cost 3. Shock mounting point

Screening

Screening narrows the candidate space using hard constraints derived directly from the design requirements: density below the 4130 baseline, base-metal yield strength above the FEA-derived minimum stress, TIG/GTAW compatibility with the team's available fabrication process, and sufficient welded-joint strength retention. The base-yield screen is used for initial material feasibility, while heat-affected-zone (HAZ) behavior is treated as a weld reliability cutoff and then revisited in validation because the final local HAZ stress depends on weld placement, geometry, and post-weld aging as shown in Table II.

Table II. Filters narrowing the material candidate space for the control arm.

Constraint	Symbol	Threshold	Justification
Density	ρ	$< 7.85 \text{ g/cm}^3$	Weight-reduction target; 4130 retained only as baseline
Base yield strength	$\sigma_{y,\text{base}}$	$\geq 304.47 \text{ MPa}$	FEA-derived minimum for initial material screen
HAZ retention	$R_{\text{HAZ}} = \sigma_{y,\text{HAZ}} / \sigma_{y,\text{base}}$	≥ 0.70	Ensures practical welded-joint strength after aging
Team-shop weldability	TIG/GTAW	Required	Must be compatible with available filler/process controls

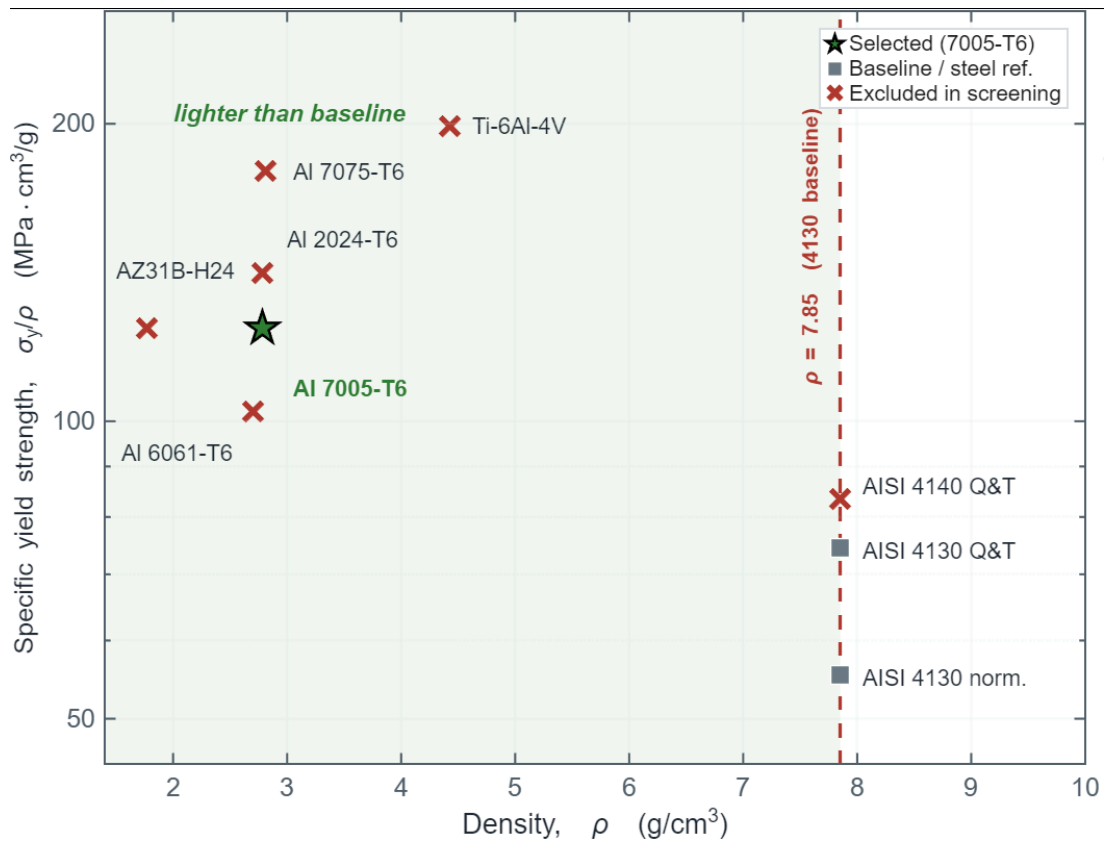


Figure 6. Ashby plot for specific yield strength (MPa·cm³/g) vs. density ρ (g/cm³). The density threshold is drawn at the 4130 baseline; 4130 remains shown as a reference rather than a weight-reduction candidate.

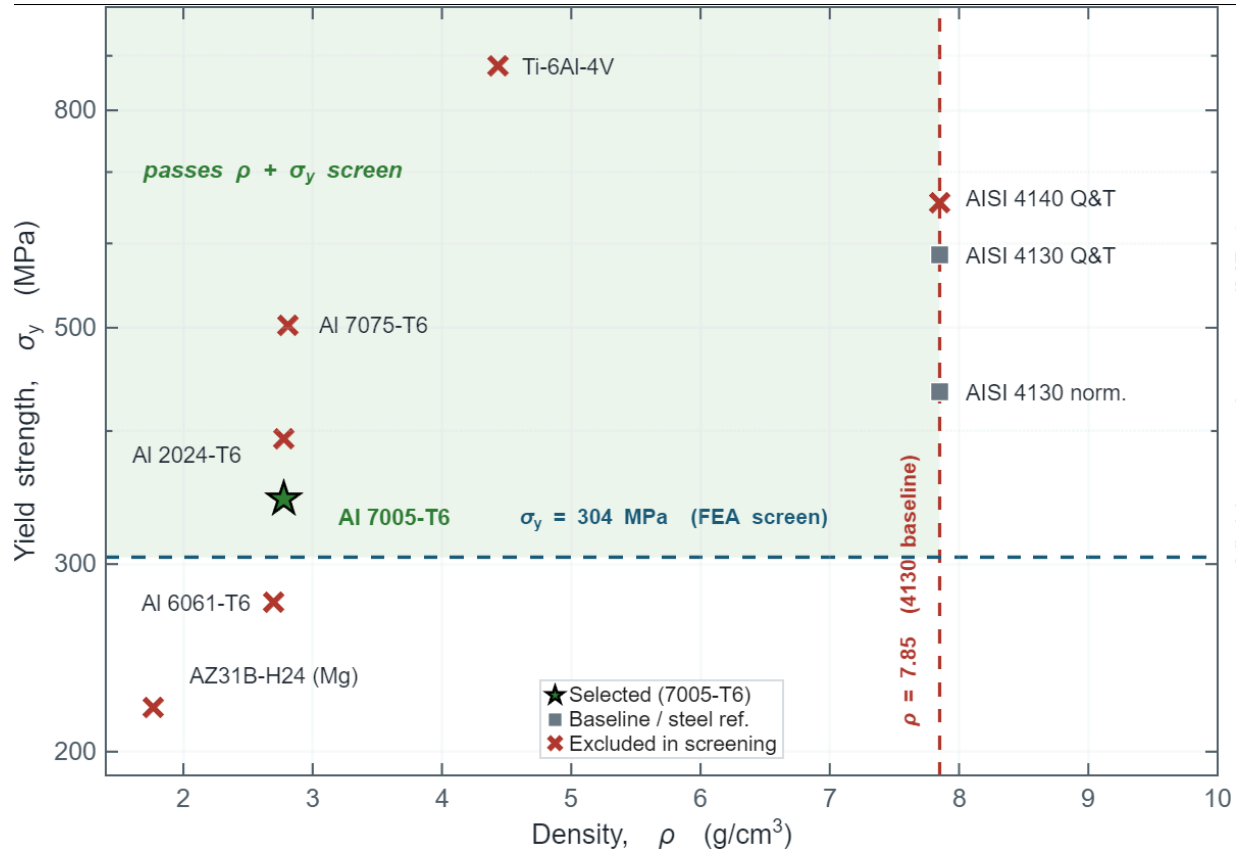


Figure 7. Ashby plot for yield strength σ_y (MPa) vs. density ρ (g/cm³). The vertical threshold denotes the 4130 density baseline and the horizontal threshold denotes the FEA-derived base-yield screen from Table II.

Figures 6 and 7 show the quantitative density and base-yield screens. Because weldability and HAZ retention are not direct x-y variables in these plots, the circled or labeled points should be interpreted together with Table II. In particular, 4130 is retained as a baseline reference, while 7005-T6 is the only aluminum replacement material that satisfies the density, base-yield, weldability, and HAZ-retention requirements.

Applying the revised filters to the candidate dataset (5XXX, 6XXX, 7XXX, and 2XXX aluminum series; 4130, 4140, and 4340 alloy steels; 304/316/17-4 PH stainless steels; CP Ti and Ti-6Al-4V; AZ31B/AZ80A magnesium) produces the following outcome:

- Al 7005-T6 — $\rho = 2.78$ g/cm³, $\sigma_{y,base} = 345$ MPa, $R_{HAZ} \approx 0.84$, TIG-weldable with 5356 filler; retained as the leading replacement material.
- AISI 4130 normalized and 4130 Q&T — retained as baseline/steel references, but not preferred replacement materials because they do not reduce density relative to the existing design.
- Al 6061-T6 — weldable and easy to machine, but excluded from final selection because $\sigma_{y,base} = 276$ MPa is below the 304.47 MPa screen and R_{HAZ} is substantially lower than 7005.

- AISI 4140 Q&T — high strength, but excluded from final selection because it requires tighter preheat/post-weld controls than the team-shop process assumed in this screening.

Other high-strength alloys, including 7075-T6, 7075-T73, 2014-T6, 2024-T6, 4340 Q&T, 17-4 PH H1025, and Ti-6Al-4V, are not eligible for the final selection under the team-shop weldability assumptions. Low-density options such as AZ31B-H24 and several 5XXX/6XXX aluminum alloys are excluded by the base-yield and/or HAZ-retention cutoffs. These materials are still useful comparison cases in ranking because they illustrate why high catalog strength or low density alone is insufficient for a welded control arm.

Ranking

After screening, ranking is used to compare the feasible replacement material against the steel baseline and several excluded comparison materials. The Figure of Merit is based on welded-joint load capacity per unit density and a normalized machining factor (Eq. 1). This keeps the ranking tied to the design objectives of weight reduction, welded strength, and manufacturability, while avoiding the inconsistency of using HAZ yield as the only initial screening cutoff.

$$\text{FoM} = (\sigma_{y,\text{HAZ}} / \rho) \times (\text{HV}_{\text{ref}} / \text{HV}) \quad (1)$$

In Eq. 1, $\sigma_{y,\text{HAZ}} / \rho$ is the specific yield strength of the welded heat-affected zone, and $\text{HB}_{\text{ref}} / \text{HB}$ is a normalized machinability factor relative to 4130 normalized steel, with $\text{HB}_{\text{ref}} = 217$. The additional screening cutoff $R_{\text{HAZ}} = \sigma_{y,\text{HAZ}} / \sigma_{y,\text{base}} \geq 0.70$ prevents a material from ranking highly only because of low density if it loses too much strength after welding. This structure is reasonable for the control arm because the part is welded, machined, and weight-sensitive. Lower hardness reduces cutting forces, tool wear, and fabrication time, while higher HAZ yield strength improves the load-bearing capacity of the joint after welding and aging. Materials that fail screening are therefore included in Table III only as non-eligible references, not as final candidates.

Table III evaluates Eq. 1 across the selected material and the steel baseline, and several comparison materials. Materials marked with an asterisk fail one or more screening constraints and are reported only for context. The selected material, Al 7005-T6, is highlighted.

Table III. Figure-of-Merit ranking. Green highlighted row = selected material. R_{HAZ} is shown in the status column where relevant.

Material	ρ (g/cm ³)	σ_y (MPa)	$\sigma_{y,\text{HAZ}}$ (MPa)	HB	Status	M
Al 7005-T6 (selected)	2.78	345	290	119	Pass $R=0.84$	198
AISI 4130 normalized	7.85	435	410	226	Baseline $R=0.94$	52
AISI 4130 Q&T	7.85	585	555	250	Steel ref. $R=0.95$	64
Al 6061-T6*	2.70	276	131	107	Fails σ_y $R=0.47$	102
AISI 4140 Q&T*	7.85	655	620	292	Fails shop	61
Ti-6Al-4V*	4.43	880	750	349	Fails shop	110
Al 7075-T6*	2.81	503	50	175	Fails weld $R=0.10$	23
Al 2024-T6*	2.78	393	39	142	Fails weld $R=0.10$	22
AZ31B-H24 (Mg)*	1.77	220	110	73	Fails σ_y $R=0.50$	192

Al 7005-T6 ranks first among the eligible replacement materials, with FoM ≈ 216 . Its advantage comes from combining low density, adequate base-metal yield strength, strong estimated HAZ retention after aging ($R_{\text{HAZ}} \approx 0.84$), and low Brinell hardness relative to the 4130 baseline. Compared with 4130 normalized and 4130 Q&T, 7005 scores roughly three to four times higher because the steel options carry a 7.85 g/cm³ density penalty in the $\sigma_{y,\text{HAZ}} / \rho$ term.

The comparison materials show why the additional cutoff is necessary. Al 7075-T6 and Al 2024-T6 have high base yield strengths, but their effective welded-joint strength is reduced by hot-cracking susceptibility and poor TIG-weldability, so they fail the weldability/HAZ-retention requirement. Ti-6Al-4V scores well numerically but is excluded because the team lacks the inert-atmosphere welding controls needed to avoid oxide-related weld degradation. AZ31B-H24 magnesium scores well by density and hardness, but it fails the base-yield screen at $\sigma_y = 220$ MPa and does not provide sufficient margin for the FEA-derived stress requirement.

Table IV. Properties of 4130 Steel, 6061 and 7005 Aluminum [2, 15, 16].

Properties	4130	6061	7005
Density	7.85 g/cm ³	2.7 g/cm ³	2.78 g/cm ³
Melting Point	1432°C	588°C	607-643°C
Tensile Strength	560 MPa	310 MPa	390 MPa
Yield Strength	460 MPa	276 MPa	345 MPa
Shear Strength	80 GPa	207 MPa	300 MPa
Elastic Modulus	190-210 GPa	68.9 GPa	72 GPa
Poisson's Ratio	0.27-0.30	0.33	0.33
Elongation at Break	21.5%	12-17%	15%
Brinell Hardness	217	95	105
Thermal Conductivity	42.7 W/mK	167 W/mK	137 W/mK

Among the aluminum alloys considered, 7005 and 6061 are the most practical weldable references because both can be TIG welded with appropriate filler selection and both are precipitation-strengthened alloys. However, 6061 is retained only as a comparison material because its base yield strength, 276 MPa is below the 304.47 MPa cutoff [15]. In contrast, 7005 combines $\sigma_{y,base} = 345$ MPa with higher HAZ strength retention, so it remains the selected material [16]. Because this selection depends on post-weld recovery, the following validation section evaluates whether welded and aged 7005 can recover sufficient HAZ strength for the final stress state predicted by FEA.

Validation

To verify that the stock from Fairing Industrial matched that of 7005 specifications, X-ray fluorescence (XRF) spectroscopy was performed on both the billet and tube samples in accordance with ASTM B985-12 [17]. Measurements were taken using an Oxford Instruments X-MET5100 handheld XRF analyzer, with each sample's surface ground to remove the oxide layer prior to scanning to minimize measurement error. Multiple readings were averaged across each sample face to account for local compositional inhomogeneity. This compositional check is critical, since the strengthening response of 7005 to the subsequent heat treatment is directly tied to the Zn and Mg content driving $MgZn_2$ precipitate formation; any significant deviation from specification would invalidate the planned aging protocol [18].

Welded test specimens were prepared in accordance with AWS D1.2, the structural welding code for aluminum [19]. Two 3/8" thick 7005-T4 plates were joined using a double-V (X-shaped) groove geometry, with each plate edge prepared with a 45° knife-edge bevel and the joint set with a 1/16" root gap. The X-groove configuration permits symmetric weld passes from both faces of the plate, minimizing angular distortion and ensuring full penetration through the joint thickness. Welding was performed via alternating-current tungsten inert gas (AC TIG) at 125 A using AWS ER5356 (Al-5%Mg) filler rod, the standard filler alloy for welded 7005 structures [5]. A 2% lanthanated tungsten (blue-banded) electrode was selected for its stable arc characteristics and resistance to contamination at the working amperage. Four total passes were used (two on each face) to fully fill the X-groove. Argon shielding gas was used to prevent oxidation of the molten weld pool, and the AC current waveform provided cathodic cleaning of the surface oxide layer.

Our heat treatment procedure for the 7005 welded samples will attempt to bring the post-welded sample to an artificially-aged T6 temper. This will follow the precipitate metallurgical theory as well as ASTM standards for aging. After welding, we expect the immediate microstructure to be at, functionally, a T0 temper. We have the option, now, of solution-treating the welded samples. This can occur by holding our welded 7005 sample at 470 C before immediate water quenching [20]. After this homogenizing step, we expect a supersaturated solid solution (SSSS), where there are minimal precipitates. Our analyzed samples did not undergo this treatment. Manufacturer specifications from *Fairing Industrial* indicated a presence of Zr. In 7xxx alloys, Zr controls the grain size by forming Al_3Zr dispersoids that control grains via Zener pinning [21]. However, these precipitates are mostly dissolved in the weld pool, while remaining intact in the bulk material. Al_3Zr precipitates slowly compared to GP and η' phases, so a solution treatment would grow the grains in the weld pool, where Zr dispersoids are absent, causing a difference in the grain sizes between the weld and the bulk.

If we leave the sample, then, to naturally age (on the order of weeks), we will recover a T4 temper, which retains some strength due to the precipitated GP zones [22]. However, we seek a T6 temper for the semi-coherent η' phases, which have a significant impact on strength due to the localized lattice distortion. Care must also be taken not to exceed aging lengths or temperatures to avoid the transformation of η' into incoherent η phases, which do not distort the lattice and thus lose effective strength.

To do this, we first start by culturing the GP zones through a 93 C (200 F) soak for 6 hours. This temperature allows thermal activation for nucleation of precipitates, while keeping diffusion and elemental segregation at a minimum, to allow for maximum preprecipitate count. The second step, following nucleation, is a high-temperature soak at 160 C (320 F). This enables the transformation of GP zones into the coherent η' phases, yielding the desired strengthening mechanism. These heat treatment steps were recommended by *Fairing Industrial* and ASTM B221/B918 standards for aluminum heat treatments [23, 24].

To determine the efficacy of our treatment, we prepare three samples. The first is the base 7005 billet material, which comes in a T4 temper. This will serve as a control. The second is the post-welded sample that undergoes no heat treatment. This sample will tell us the effect of welding while serving as a control for the heat treatment. The final sample will be a welded treated piece. This sample will represent the properties of our designed arm and will be the ultimate indicator of the success of our treatment. Table V shows the treatments, as well as the expected microstructure.

Table V. Samples and expected microstructures.

	Sample 1	Sample 2	Sample 3
Material	Bulk AA 7005-T4	Welded, untreated 7005-T0	Welded, artificially aged 7005-T6
Expected microstructure	GP, extrusion marks	SSSS, η (overaged)	GP/ η'

Sample 1 is the bulk material, which comes in a T4 temper. This natural aging procedure, we expect, to yield GP zones, since not enough thermal activation is enough to progress the precipitation cycle to form η' or η phases. In Sample 2, the post-welded piece, we expect to see an SSSS phase, since the weld pool will solidify, trapping excess Zn and Mg atoms in the matrix without a chance to precipitate. Due to lack of a solution treatment, we also expect areas of slower cooling rate to contain overaged η regions. In Sample 3, we expect full dissolution of all precipitates before the artificial aging step, theoretically yielding a concentration of GP zones and semicoherent η' phases to maximize strength.

Following welding and any applicable heat treatment, samples for microstructural characterization were prepared per ASTM E3, the standard guide for the preparation of metallographic specimens [25]. Specimens were sectioned transverse to the weld direction to expose the bulk material, heat-affected zone (HAZ), and weld pool in a single field of view. Cut samples were cold-mounted in epoxy and ground sequentially with SiC papers from 320 to 1200 grit, followed by polishing with diamond suspensions and a final 0.3 μm alumina slurry, with etching performed with Keller's reagent (2.5 mL HNO_3 , 1.5 mL HCl , 1.0 mL HF , 95 mL H_2O), applied via swabbing for 10–20 seconds, and then rinsed with deionized water and ethanol to halt the reaction. Etched samples were then analyzed using an optical microscope (OM) and a Hitachi SU3900 scanning electron microscope (SEM) equipped with EDS for localized elemental analysis.

Mechanical evaluation of the base material, welded-untreated, and welded-treated samples was planned in accordance with ASTM E8/E8M room-temperature tensile testing

procedures using an Instron testing machine [26]. Due to limited stock dimensions, dogbone specimens were manually milled rather than waterjet cut. The specimens were designed based on ASTM E8/E8M subsize geometry, maintaining the standard gauge-length-to-width ratio (4:1), but did not fully conform to the prescribed dimensions. Two specimen sizes with overall lengths of 2.70 in and 1.80 in were used, compared to the ASTM subsize overall length of 4.00 in. The specimens were approximately 0.3 in thick, exceeding the nominal ASTM subsize thickness of 0.250 in. Due to time constraints, these specimens could not be machined further, preventing tensile testing from being performed successfully.

Vickers microindentation hardness testing was performed on the dogbone specimens in accordance with ASTM E384 [27]. A 136° diamond pyramid indenter was applied at a 50 gf load with a 15 s dwell time, with both diagonals (d_1 , d_2) measured optically and Vickers hardness calculated as $HV = 1.8544 \cdot F / d^2$, where F is in gf and d is the mean diagonal in μm . Following polishing, hardness measurements were taken at 4 mm intervals along the longitudinal centerline of each specimen, with the nominal 0 mm location defined as the geometric center of the dogbone. Because the specimens were geometrically asymmetric and the weld boundaries were not clearly distinguishable after preparation, hardness values were evaluated as a function of position rather than being assigned directly to the base material, heat-affected zone, or fusion zone. The resulting hardness profiles were used to identify relative softening and recovery across the weld region and to assess the effectiveness of the post-weld aging treatment. Measured hardness values were then correlated to estimated yield strength in the absence of tensile testing.

Discussion

Upon receiving the material from Fairing Industrial, our material supplier, our XRF scans showed the following compositions in Tables VI and VII. These are compared with expected concentrations according to the manufacturer's specification.

Table VI. XRF-measured elemental concentration for billet material.

Element	Concentration (wt%)	Expected Concentration (wt%)
Al	91.51	93.3
Zn	5.00	4.5
Mg	2.20	1.4
Cu	0.10	0
Mn	0.38	0.45
Cr	0.07	0.13
Fe	0.19	-
Si	0.37	-

Table VII. XRF-measured elemental concentration for tube material.

Element	Concentration (wt%)	Expected Concentration (wt%)
Al	93.15	93.3
Zn	4.67	4.5
Mg	1.39	1.4
Cu	0.11	0
Mn	0.34	0.45
Cr	0.13	0.13
Fe	0.14	-

While there are observed compositional differences in the billet and tube material, these are within expected fabrication tolerances. Magnesium and Zinc, the two elements that vary the most, are the main strengthening mechanisms; therefore, the current values meeting

expected concentrations validate the material for further testing. It is also impractical to purchase another piece of billet stock, since this material was only offered in bulk quantity and via B2B sale.

Regarding composition, reducing copper content is the primary contributor to strengthening the weld joint. Li et al., in an attempt to weld 7075 (note that 7075 and 7005 primarily differ in their copper content), see a large solidification range [28]. This is largely undesirable, since liquid films on the solid interface increase the tendency to crack. The trade-off is in strength, since 7075 has higher yield strength due to the precipitates formed with copper.

Another note regarding the XRF scans is the seeming absence of Zr. We expect concentrations of about 0.1-wt% Zr according to manufacturer specifications. Further analysis is to be performed to confirm whether Zr is present. However, if it is absent, we can revisit our heat treatment

We then analyzed the bulk section, weld pool, and the boundary via optical microscopy and scanning electron microscopy. Sample 1 contains only the bulk section. Figure 8 shows the relevant images.

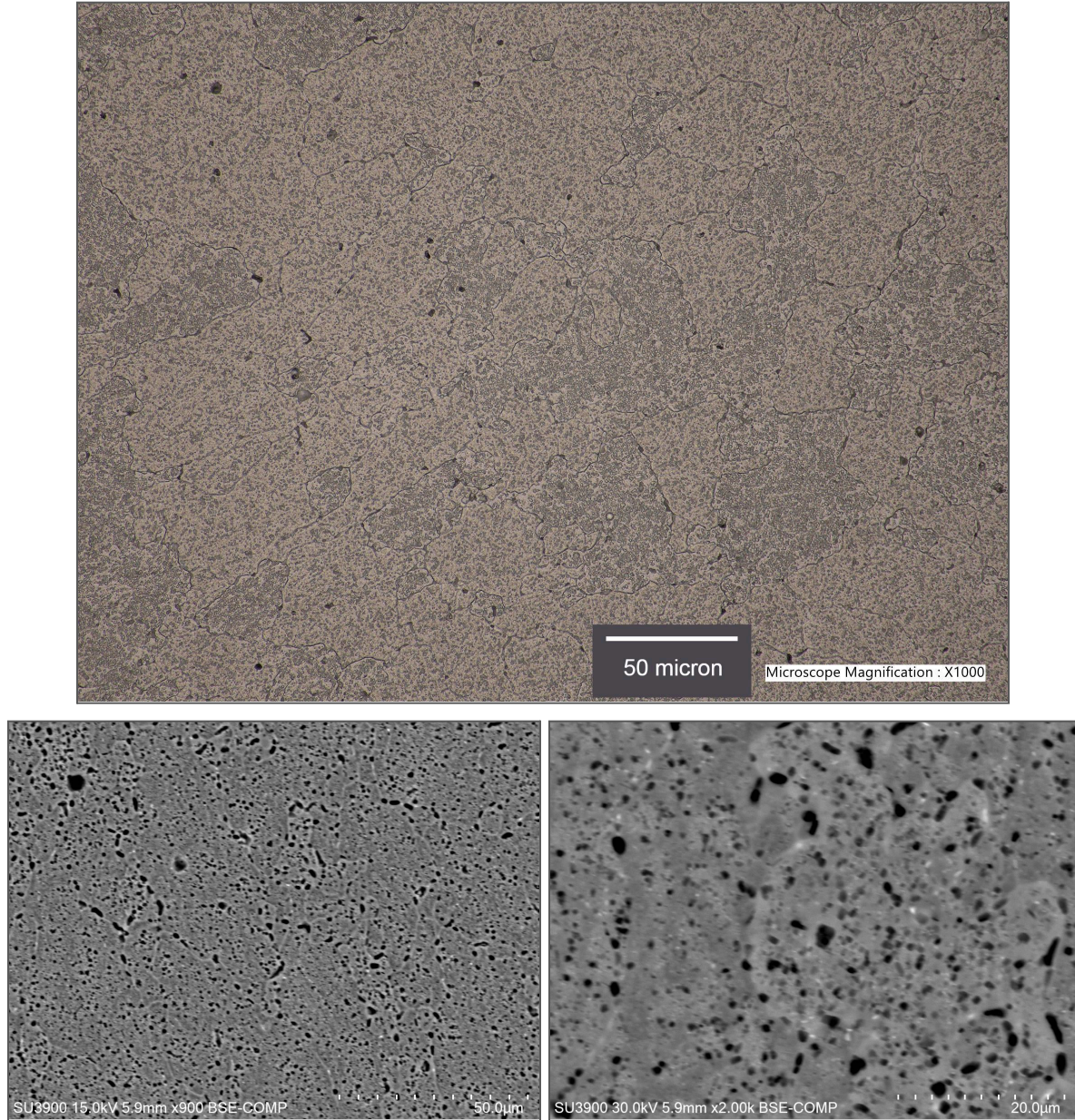


Figure 8. (a) top, (b) bottom left, (c) bottom right. OM and SEM images of bulk 7005-T4 material as-received.

The equiaxed grains are shown most visibly in Fig. 8 (a). This can be reconciled, even if the billet material was produced through extrusion. Extrusion does not guarantee a fibrous, uniaxial grain structure, especially in a material with low crystallization temperature. We can assume a recrystallization step was performed.

More importantly, we see the presence of dark freckles with diameters on the order of microns. These are best seen in Fig. 8 (b) and (c). We can eliminate GP/ η' / η phases as the identity since these particles appear on the order of tens to hundreds of nanometers, lower than the OM resolution limit. Instead, these are likely intermetallic phases with Fe and Si, both of which were recorded in appreciable quantities. A different etching behavior compared to the

bulk Al material would explain why the etch pits appear as dark spots.

Sample 2, the welded, untreated sample, reveals more information about the original structure of the bulk material. Fig. 9 shows a banded structure that reveals post-welding.

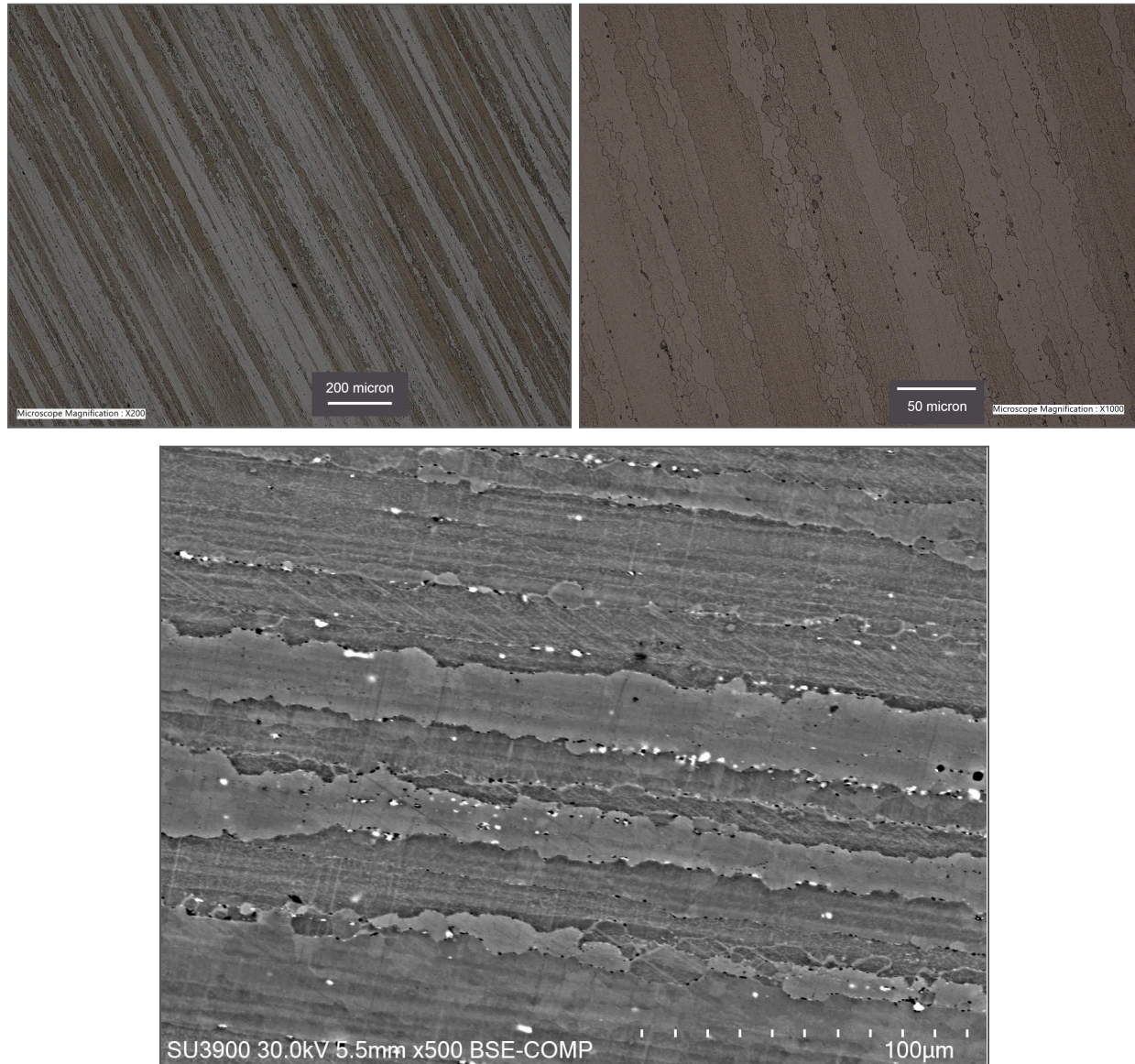


Figure 9. (a) top left, (b) top right, (c) bottom. Banded structure visible in multiple magnifications in the post-welded, pre-treatment sample.

These bands are oriented parallel away from the melt pool along the isotherm, shown in Figure 10.

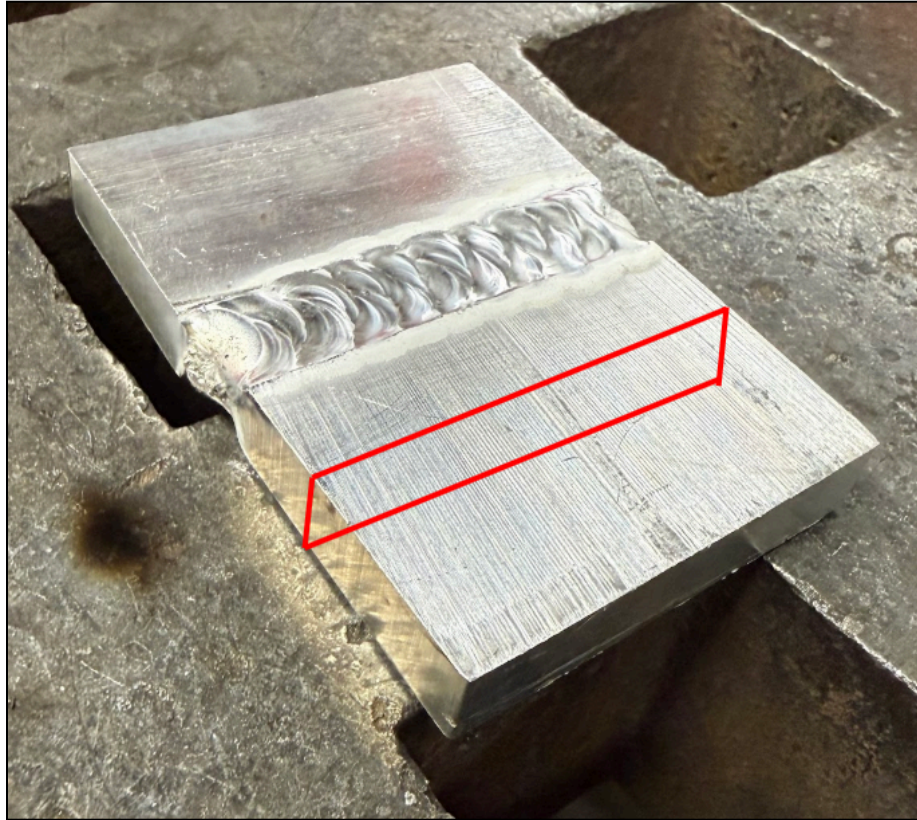


Figure 10. Planar orientation of bands away from the weld pool.

Because the bands were oriented away from the weld pool, we initially thought elemental segregation caused the intense band contrast differences seen in Fig. 9 (c). However, the width order of magnitude of bands, tens of microns, is too fine for temperatures to be notably different from band-to-band. We can revisit the effects of extrusion on the original sample to develop a new hypothesis. Knowing that welding would return the aged (T4) GP zones back into SSSS, we can deduce that this must cause the banding. GP zones take from localized Zn to form precipitates, which we determined could not be resolved in our microscopy. We therefore cannot determine the concentration of Zn in a particular region by GP zone concentration analysis. However, when the Zn within these GP zones are dissolved back into SSSS, a compositional difference must appear. Different bands with different compositions have different solvus behaviors, yielding these sharp distinctions. Essentially, the bands are hidden in the aged Sample 1 but revealed in the SSSS of Sample 2. The source of these innate Zn bands likely lies in extrusion dendrites that form during fabrication.

As we mentioned, equiaxed grains can still be present. Recrystallizing the grains after the development of these compositional bands means the new grains would conform to the old boundaries; the compositional bands would be relatively unperturbed by the new grains (i.e. would be relatively straight and not extremely jagged). Fig. 9 (b) shows this, where grains respect the incumbent compositional boundaries while maintaining equiaxed shape.

To confirm this, we attempted an EDS scan between two different bands, shown in Fig.

11. While a slight compositional difference was observed, better characterization would support the confirmation of compositional segregation.

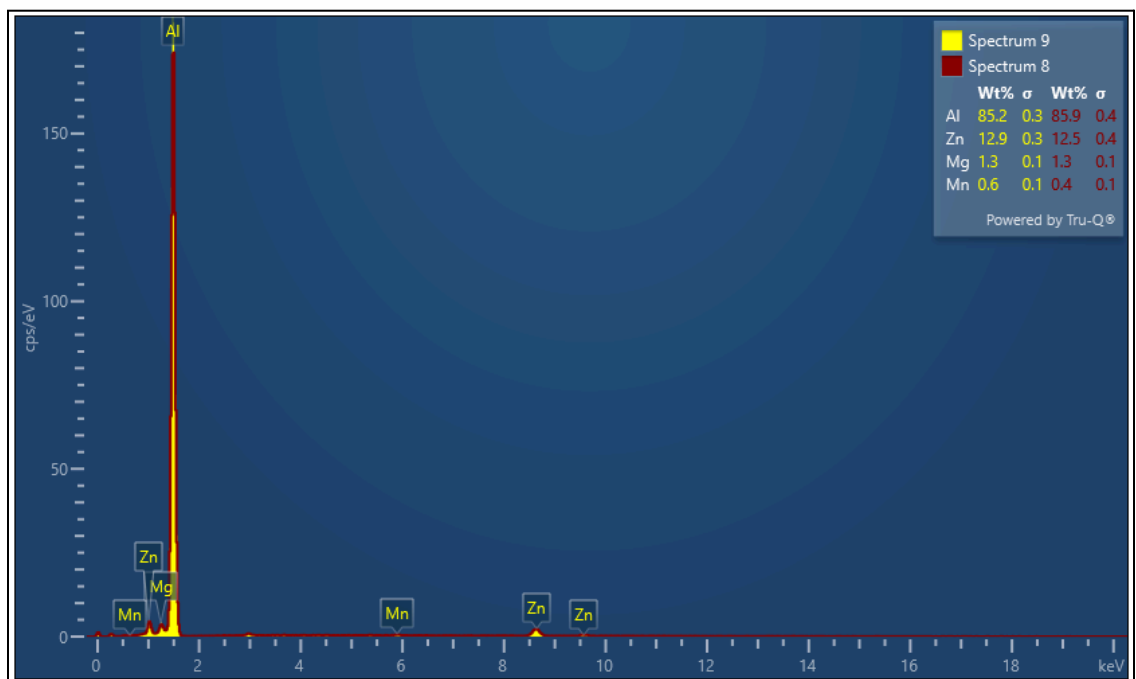
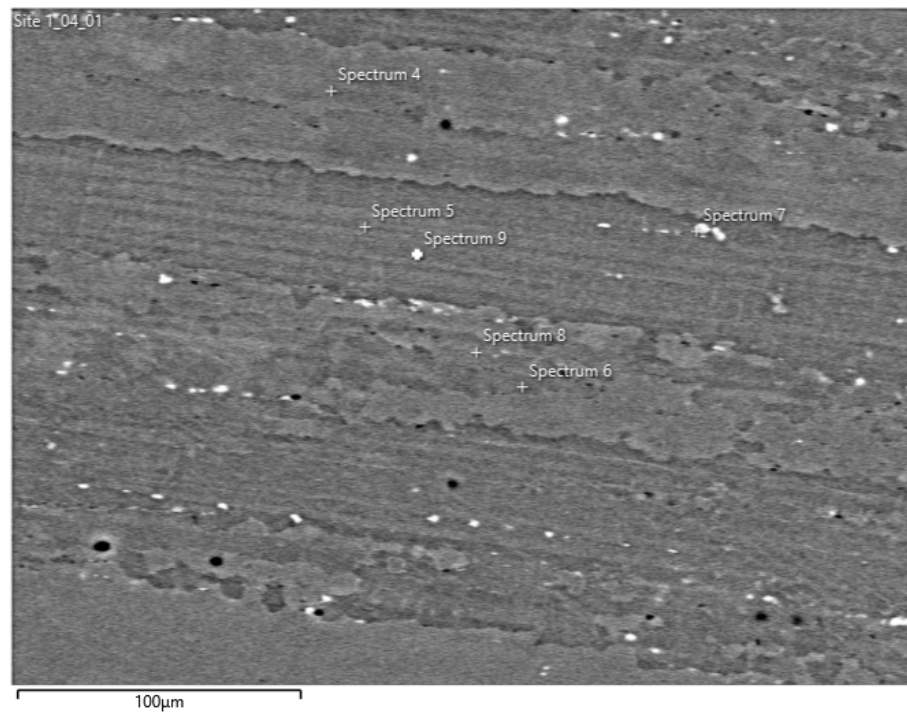


Figure 11. EDS scan indicating slight Zn composition difference between bands.

The next analyzed section of Sample 2 is the border between the bulk material and the weld pool. These images are compiled in Figure 12.

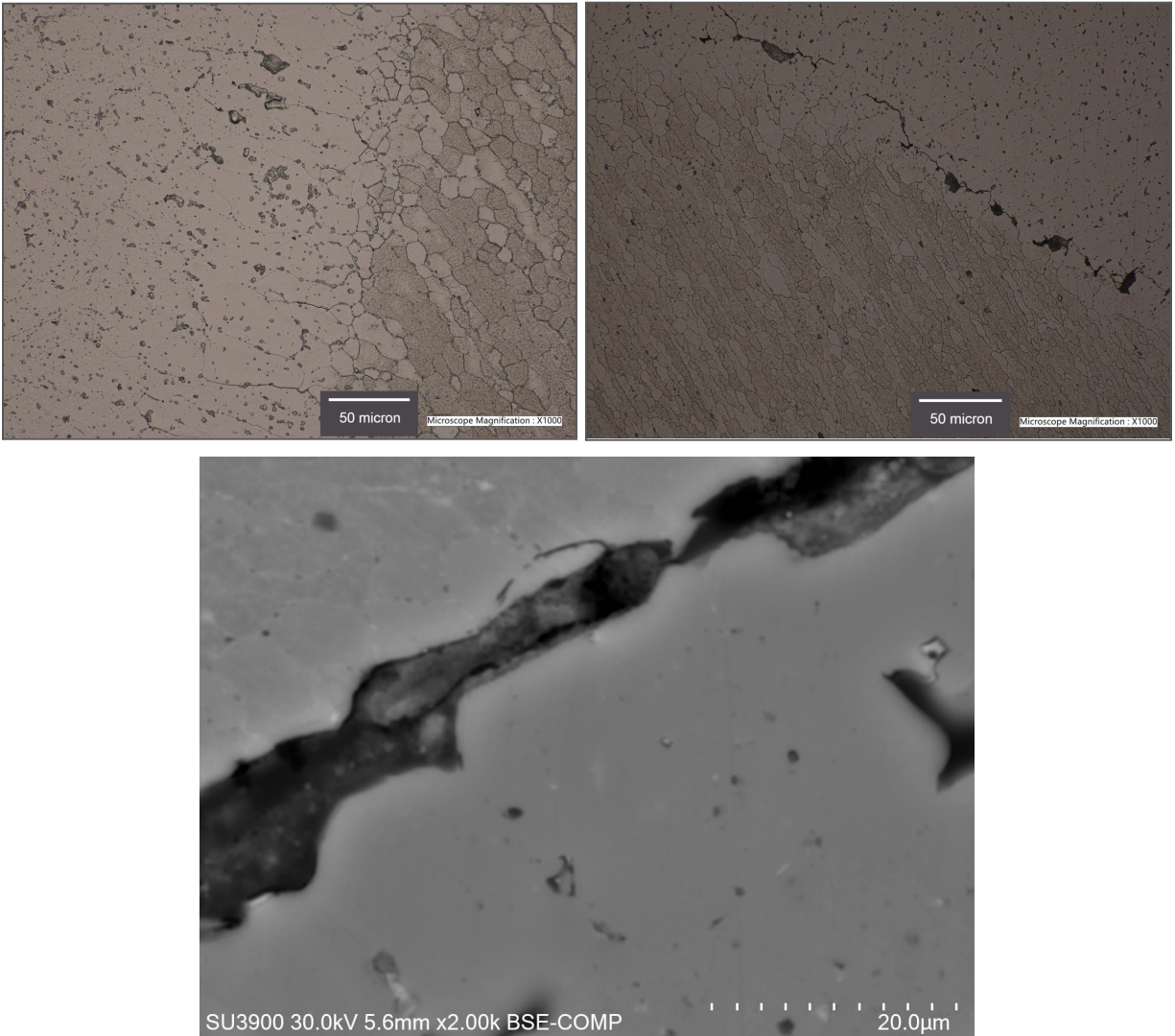


Figure 12. (a) top left, (b) top right, (c) bottom. Images of the weld pool/bulk material difference. Welding crack visible from poor penetration, grains visible in the bulk material.

Fig. 12 (a) and (b) show clearly a difference in the visibility of grains between the bulk region and the weld pool, with the bulk region having much more visible grains. This can be somewhat seen in the SEM image (c) as well. Because the weld pool is initially a fully liquid phase, the high cooling rate means the resulting solution is homogenous. The grains are still present; however, there is not enough electrochemical potential difference between them and the grain bulk. Etchant, therefore, cannot reveal the grains since it etches the weld pool uniformly.

We can also see evidence of Zr presence - more specifically, the evidence of Al_3Zr dispersoids. Comparing Fig. 12 (a) and Fig. 8 (a), we see the grain sizes are about the same order of magnitude. In this near-HAZ, the large temperatures would intuitively grow the grains; only the presence of these grain-limiting precipitates would restrict growth via Zener pinning.

We can directly compare this to the treated Sample 3. The relevant weld pool image in

Figure 13 shows the presence of much more visible grains with equivalent etching as the images in Figure 12.

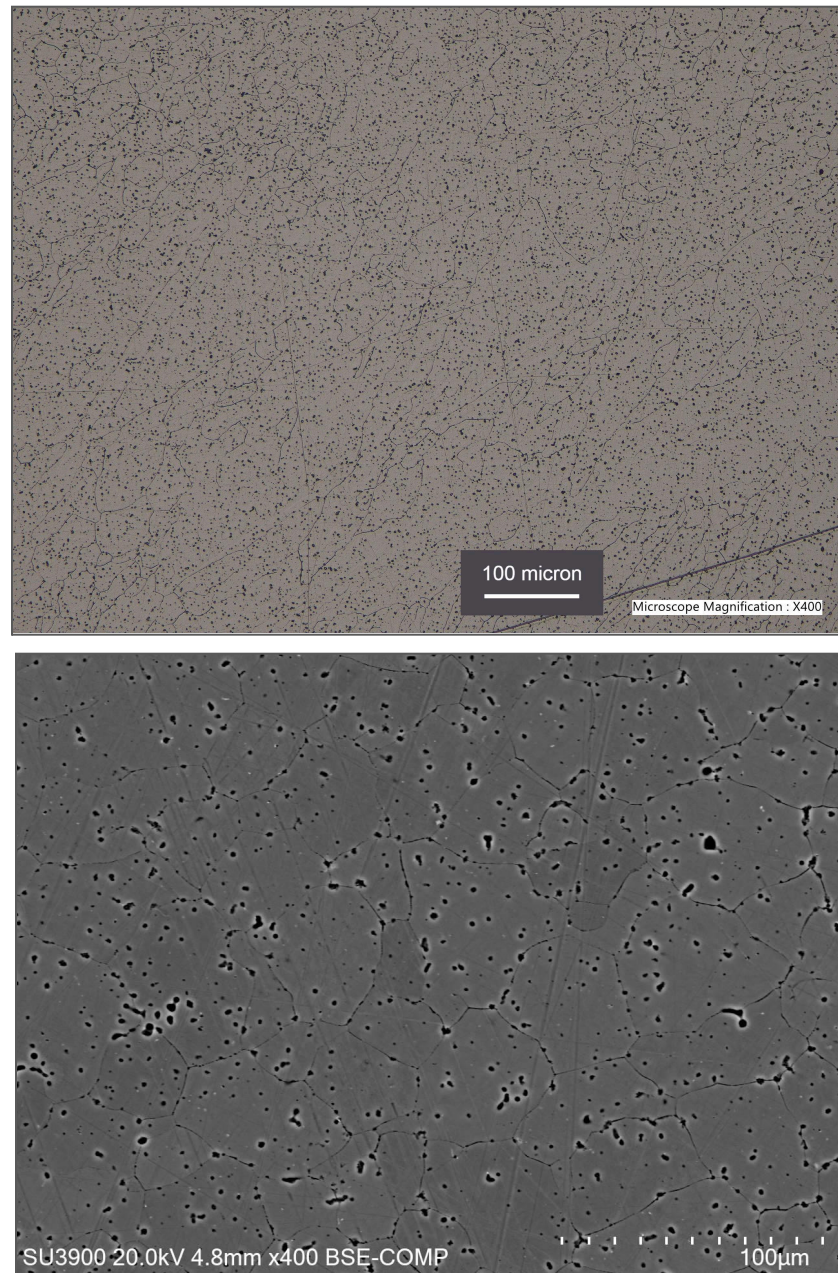


Figure 13. Visible grains within the weld pool post-treatment.

The presence of visible etching indicated a successful heat treatment. Precipitates naturally form a precipitate-free zone (PFZ) along grain boundaries; in addition to mechanical property effects, the PFZ also allows for etching to be seen much more visibly [29]. The presence of a PFZ indicates that precipitates were successfully formed within the grains.

The voids, however, indicate that proper welding protocol as outlined in AWS D1.2. Given the nature of sample preparation, this is expected. The strict qualification procedures are

too demanding for a typical student weld shop, so while we can ensure some compliance through thorough material preparation, individual joint qualification is out of scope. Hence, some porosity is expected and should be designed around.

Similarly visible is the uniform distribution of the intermetallics, represented by the black etch pits. Within the convection and Lorentz currents within the weld pool, this distribution is expected. We can now compare the grain sizes between that of the weld pool and the bulk material, done so in Figure 14.

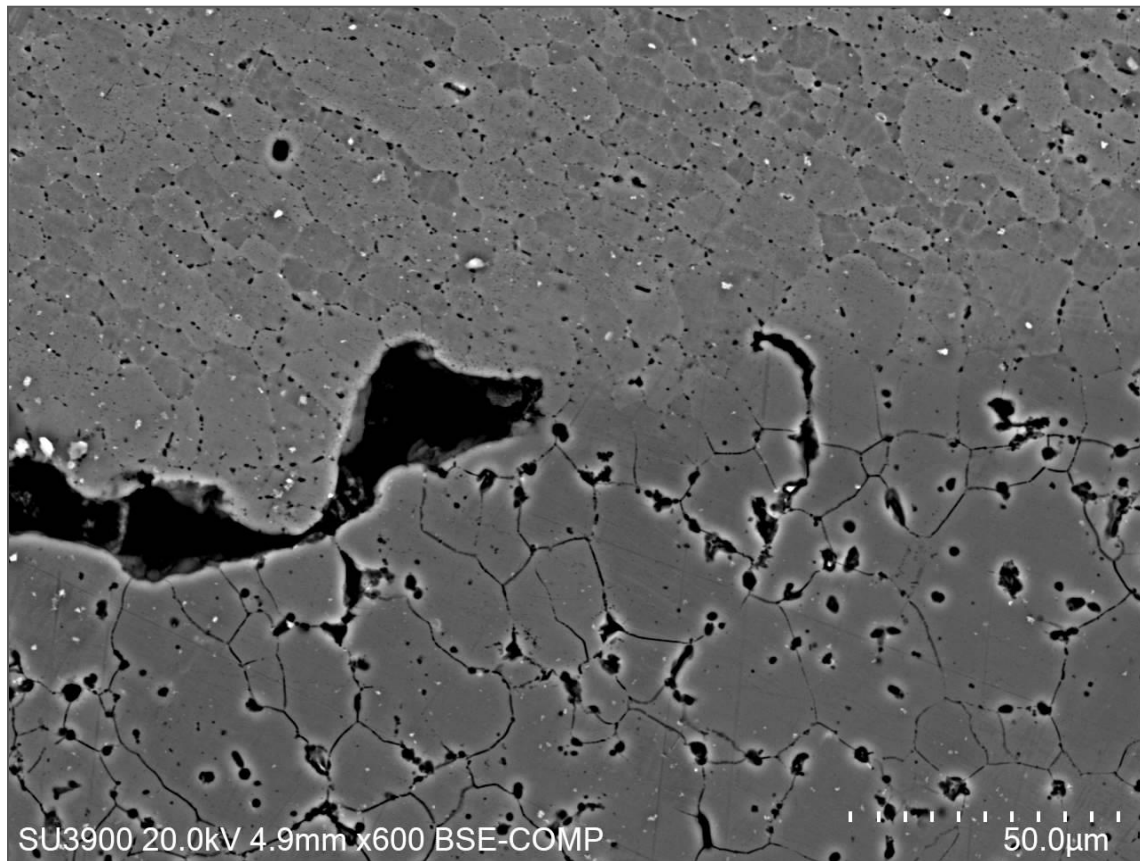


Figure 14. Junction between the weld pool (bottom half) and the bulk material (top half) for treated Sample 3.

Smaller grain size within the weld pool implies, from Hall-Petch, higher strength. However, as mentioned in our discussion on precipitates, this is not the only strengthening mechanism present. Still, visible grains are a positive indicator of the presence of precipitates.

The thicker-appearing grain boundaries in the bottom half of Figure 14 similarly indicate Mg diffusion to the boundaries, yielding a contrast difference that is expected with BSE analysis. The lighter regions surrounding the porosities, meanwhile, are likely oxide bifilms, which form from porosities and gas entrapment that cause oxide layers to fold on themselves. As aforementioned, this is a result from the stringent nature of aluminum welding that is out of

scope for a student weld shop.

The banded region in Figure 9 also evolves with the heat treatment, shown in Figure 15.

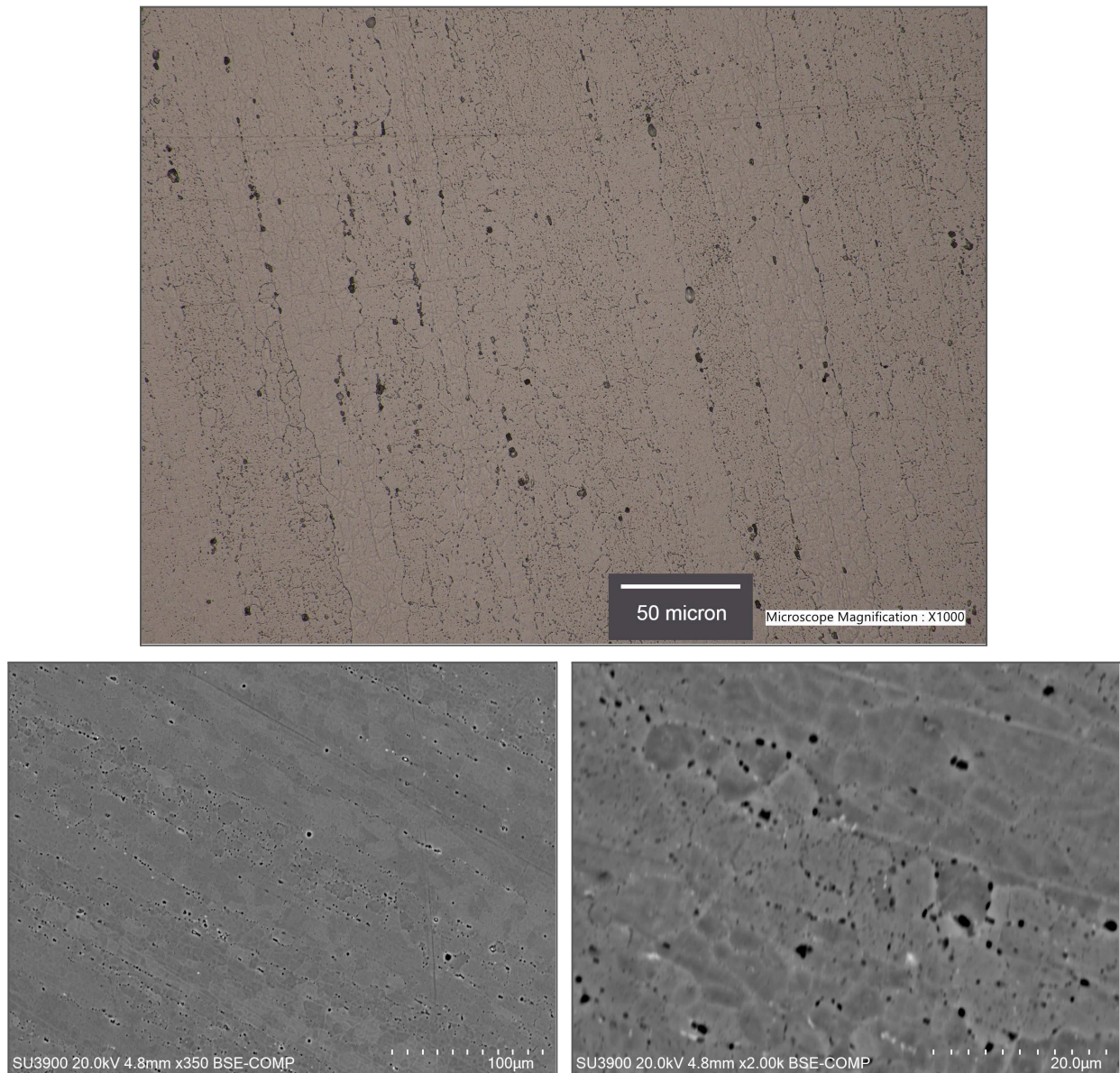


Figure 15. (a) top, (b) bottom left, (c) bottom right. Compositional band structures post-treatment.

Compared to the OM image with the same magnification in Fig. 9 (b), Fig. 15 (a) exhibits much milder contrast between bands, exhibiting a structure more akin to the equiaxed grains of Fig. 8 (a). As aforementioned, the reason we suspect extrusion/dendrite bands are not visible in the bulk T4 material are that GP zones functionally absorb the Zn, yielding a bulk material that, aside from Zn-containing GP size and concentration, is relatively homogenous in Zn content. Keller's reagent cannot show these zones, due to the nanoscale nature. In a similar manner, grown and aged GP/ η' phases from the T6 treatment would absorb most of the Zinc, leading to the dissolution of observed compositional bands. The lifespan of these bands within Samples

1-3 is tabulated in Table VIII.

Table VIII. Compositional band analysis between Samples 1-3.

	Sample 1	Sample 2	Sample 3
Band appearance	No visible bands	Visible banding	Large disappearance of bands
Explanation	GP zones mean Zn depletion within the Al-matrix, yielding uniform Zn concentration	SSSS means Zn concentration differences between bands show as contrast differences post-etching	Zn returns to precipitate form, yielding uniform distribution within the Al-matrix

Ultimately, the clearer grains and decreased intensity in the observed bands indicate a successful heat-treatment without needing to directly observe the desired precipitates; of course, the most direct way to confirm treatment efficacy is to perform TEM analysis to achieve the required resolution. Another step for analysis is to scan an unetched sample. The dark freckles present in most images, which we determined to be etch pits from prior intermetallics, would be compositionally different from the bulk matrix. Within the weld pool, however, we observe dark regions that are attributed to porosity; this result arises from insufficient welding practices, but can be considered a design constraint given the limitations of our welding capability. Still, our heat treatment can be considered qualified, and we can conduct treatments on welded prototypes.

To explore further weight reduction, a CAD model of a redesigned upper control arm was developed in Solidworks, shown in Fig. 16 (a). Unlike last year's design, which included a tab that mounted the shock on the upper control arm, the revised suspension design relocated the shock attachment to the lower control arm. This eliminates the tab and removes direct shock loading from the upper control arm. As a result, the upper control arm no longer carries significant shock forces, allowing for a lighter material selection while the lower control arm assumes the primary load-bearing role.

In order to verify that the new design satisfies the geometric constraints defined in Table I, the control arm was integrated into a suspension assembly, shown in Fig. 16(b). Within this assembly, the upper control arm does not interfere with adjacent components and maintains two chassis mounting points and one knuckle connection point, satisfying all geometric requirements.

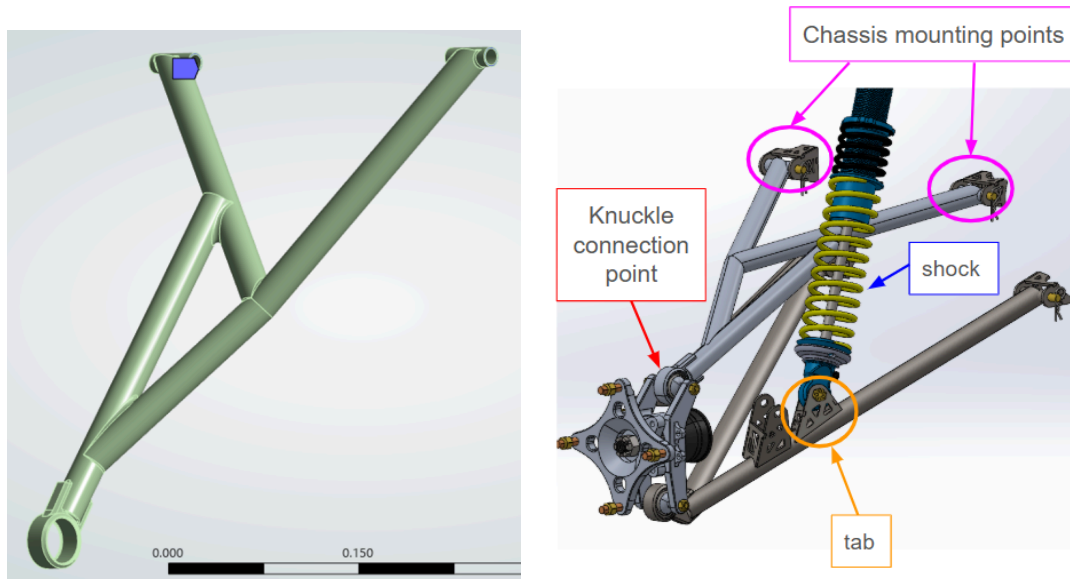


Figure 16. (a) left: CAD model of the new upper control arm design, (b) right: CAD assembly of suspension components

Validation of the new control arm design necessitated Finite Element Analysis (FEA) to be conducted in Ansys for both Al 7005 and AISI 4130 under identical loading conditions. The analysis was based on a worst-case loading scenario defined in the design requirements, which specifies a 2g event as the representative extreme condition (Table I). This loading case assumes the full load is transmitted through a single wheel into the upper control arm, which can occur during aggressive cornering, collisions with obstacles, or a rollover event.

In the FEA model, the two chassis mounting points were constrained to simulate attachment to the vehicle frame, and the load was applied at the knuckle connection point to simulate force transfer from the wheel assembly (Fig. 17).

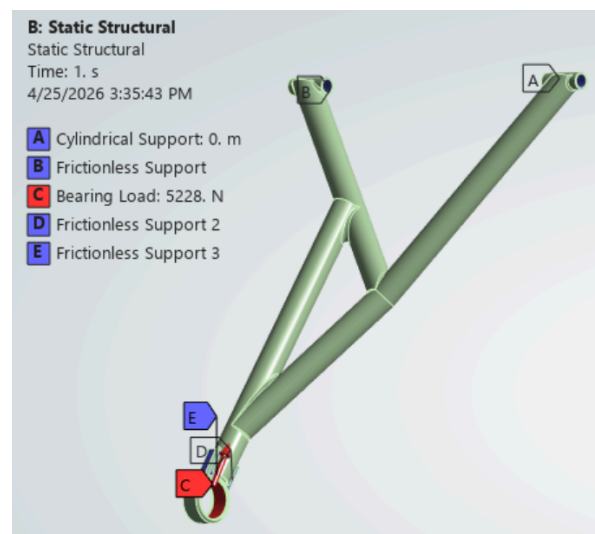


Figure 17. Finite element analysis set-up. A, B, D, and E define the boundary conditions. C is the load applied (equivalent to 1200 lbf).

The equivalent stress (von Mises) plots for both materials produce nearly identical maximum von Mises stress values, with 304.47 MPa for Al 7005 and 304.13 MPa for AISI 4130 (Fig. 18). This similarity is expected since the stress distribution is primarily governed by the geometry, boundary conditions, and applied loading rather than the material properties. Based on the Al 7005 results in Figure 18 (a), the maximum von Mises stress of 304.46 MPa was used to define the minimum required yield strength for the design constraints, ensuring a factor of safety greater than 1 under the worst-case loading condition.

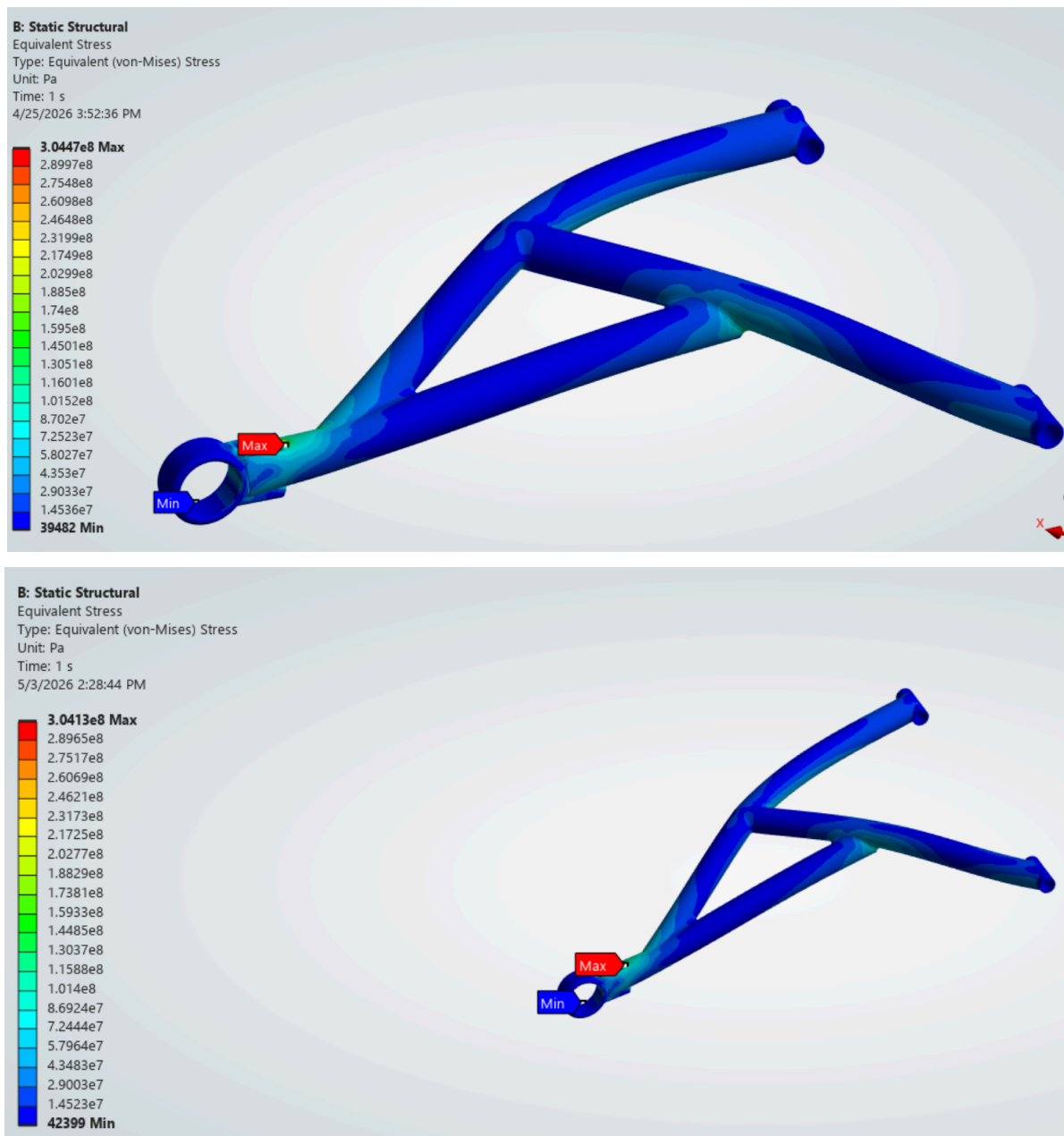


Figure 18. (a) top: 7005-T6 material applied, (b) bottom: AISI 4130 material applied. Equivalent stress (von Mises) stress plots, with maximum stress values shown on the left.

The FEA results were further evaluated using factor of safety (FOS) plots for both materials under the same 2g loading condition, as shown in Fig. 19. The Al 7005 design exhibited a minimum factor of safety of 1.0182 while the AISI 4130 design resulted in a higher factor of safety of 1.6697. Since both designs have the same geometry and experience the same loading, the higher factor of safety in 4130 is a direct consequence of its higher yield strength. However, this increased safety margin in 4130 indicates that it carries excess strength that is not required by the design requirements defined in Table I, which specify a minimum factor of safety greater than 1.

In contrast, Al 7005 operates much closer to the required safety threshold while still maintaining structural integrity. Given that our primary objective is to minimize weight, the 7005 design is deemed appropriately optimized to avoid excessive material usage while still meeting performance requirements.

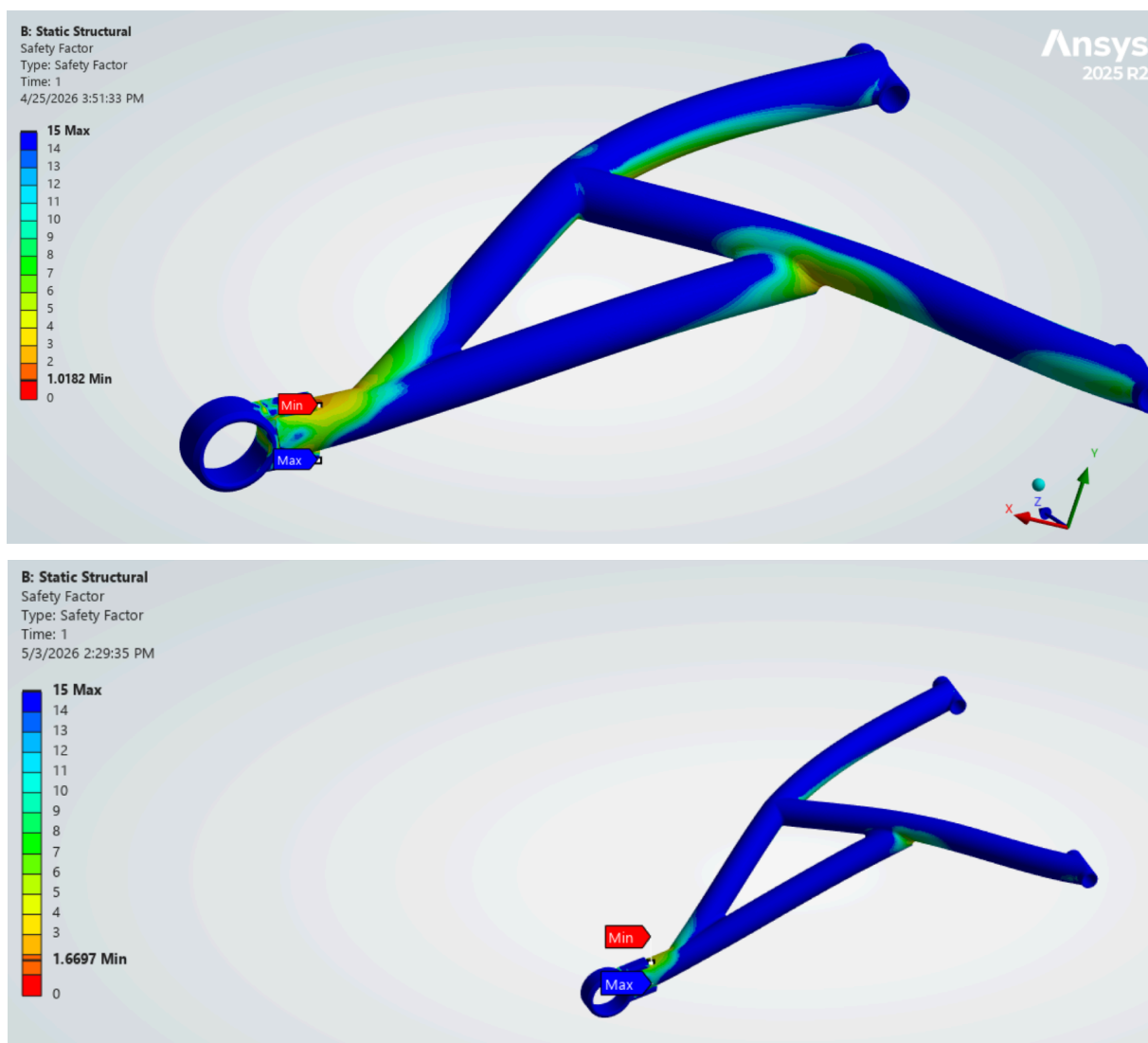


Figure 19. (a) top: Al 7005 applied and (b) bottom: AISI 4130 applied. Factor of safety contour plots, with minimum factor of safety values shown on the left.

In a similar manner, we can analyze the effects of a frontal impact. Where Figures 16-19 demonstrated a compressive force into the bulk of the arm (simulating a rollover event), another relevant force is the frontal impact force, shown in context of the assembly in Figure 20. This is slightly more difficult to model within FEA. Because of the nature of mesh discretization within finite element methods (coupled with the fact that student licenses for SolidWorks, Ansys, etc. often have mesh sizes that are too large), singularities and regions of excessively overestimated/underestimated stresses invalidate our results. To counteract this, we conduct frame analysis on the model, shown in Figure 21.

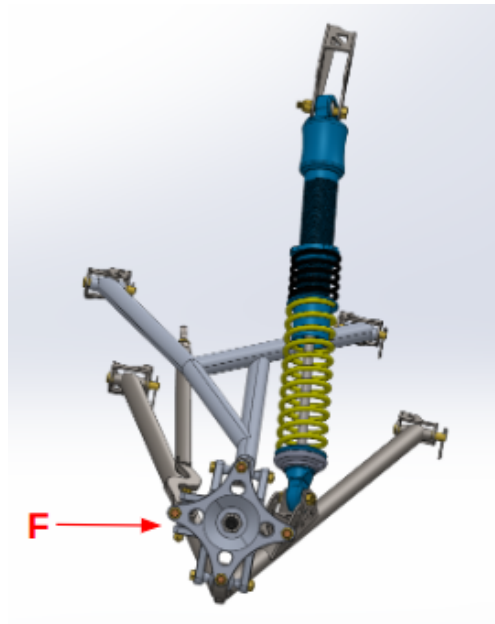


Figure 20. Incident frontal impact load.

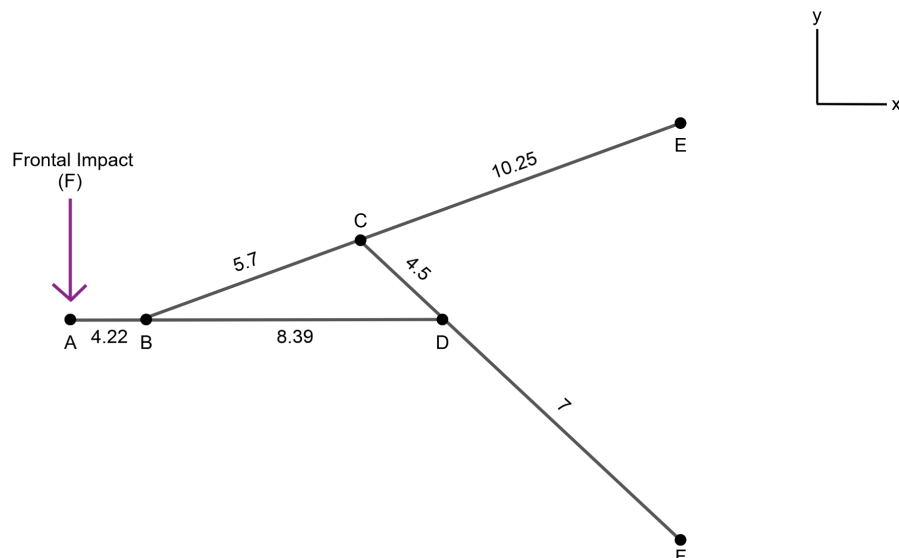


Figure 21. Frame assumption, bird's-eye view.

Within Figure 21, there are force reactions (in the x- and y-directions) on each of the points (except A), with moment reactions at points E and F (the chassis mounting points). This yields 12 unknown variables (except F, which we can assume to be a constant). By writing each static analysis equation, we can then generate twelve equations, creating a fully constrained system of variables. These equations are compiled in Table IX.

Table IX. System of Equations for the frame in Fig. 21. Each row equals 0 in static analysis.

EQ.	Bx	By	Cx	Cy	Dx	Dy	Ex	Ey	Fx	Fy	M.E	M.F	F
1								1		1			-1
2							1		1				
3							-12.5				1	1	18
4	1		1				1						
5		1		1				1					
6	4.92	-4.92					-5.16	8.39			1		
7	1				1								
8		1				1							1
9		-4.92											9.14
10			1		1				1				
11				1		1				1			
12			7.34	-8.86	4.47	-5.39						1	

Performing the linear algebra, we achieve the following list of variables, measured relative to the incident force F, in Table X.

Table X. Measured reaction forces at each point. Note that units are in inches, which only affects M_E and M_F , which will be in units of in·lbf.

Variable	Value
B_x	$-3.03F$
B_y	$1.86F$
C_x	0
C_y	$-F$
D_x	$3.03F$
D_y	$-0.86F$
E_x	$3.03F$
E_y	$-0.86F$
F_x	$-3.03F$
F_y	$1.86F$
M_E	$46.85F$
M_F	$-27.01F$

This is important for failure analysis, where we can pick specific reaction forces for subsequent FEA. We note that the primary failure mode is point D on member CF. The resulting inwards force will act as a 3-point bend. Taking D_x and D_y in the original coordinate axes, we can apply the force with direction onto member CF in the FEA simulation shown in Figure 22.

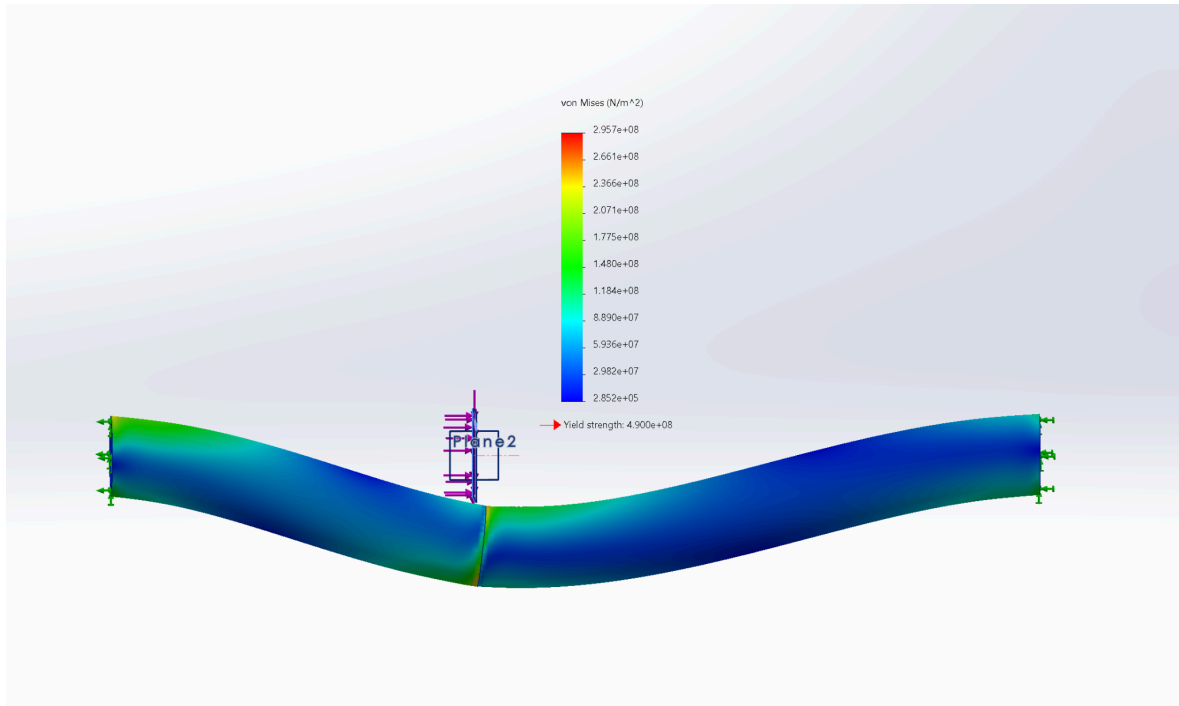


Figure 22. Frontal impact equivalent force FEA simulation on member CF. Maximum stress 296 MPa.

The observed stress is ultimately under the maximum stress for a side impact, outlined in Figure 18a to be 304 MPa.

The theoretical mass of the 4130 control arm and 7005 control arm, taken from Ansys, are 3.117 lb and 1.154 lb, respectively. Although both theoretical masses are both lighter than last year's control arm, satisfying the material constraint in Table I, the 7005 control arm is significantly lighter, aligning with the primary objective of weight reduction. With the new design, we achieve a 63.4% weight reduction.

Ultimately, although AISI 4130 provides a higher safety margin, Al 7005 is preferred as it satisfies the design requirements with significantly lower material usage and improved strength-to-weight efficiency, which will translate to enhanced suspension performance.

After analyzing theoretical performance and validating baseline material strength, we manufactured a prototype. The process is shown in Figure 23.



Figure 23. Manufacturing process. (a) top left shows the wafer CNC process. (b) top middle shows the jigging system. (c) top right shows part of the welding process. (d) bottom left shows the fully welded arms. (e) bottom middle shows the heat treatment step. (f) shows the finished product on the Baja SAE vehicle.

Figure 22f shows the arm fitting within the chassis mounting points, indicative of the geometric design requirement fulfillment. It is difficult to design a testing fixture to test the side impact or frontal impact loads outlined in Figures 17 and 20, so field testing (and competition performance) was used as a qualitative metric.

During the manufacturing process, however, AWS D1.2 purity standards were difficult to meet, given the nature and limitations of the student weld shop, as aforementioned, during our tensile samples. In addition, the precise nature of tube fit-up within the jig was not feasible given the tolerancing within our notching setup. Therefore, flush fits were uncommon, and instead we often had to weld over gaps of up to $\frac{1}{8}$ ". Still, our design did not exhibit failure at the welded joints - rather, material failure dominated, as explored in Figures 17 and 20.

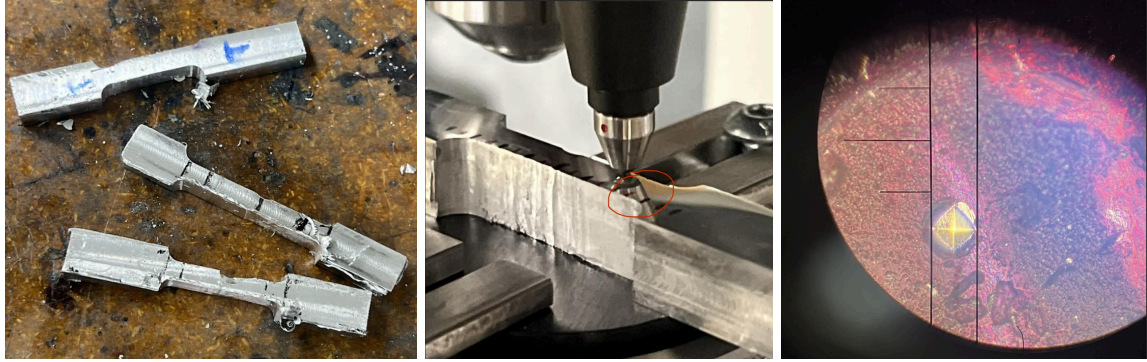


Figure 24. Dogbone samples and testing. (L) Shows the samples after manual milling. (M) Shows the pen markings on the sample denoting relative locations of indentation. (R) Shows the indentation under microscope.

Along with the prototype, dogbone-shaped samples of the base material, untreated welded joint, and aged welded joint were created for tensile testing and hardness testing. The original plan was to waterjet the dogbone samples, but the stock used was cut far too short to be waterjetted; each sample was cut out manually instead. Figure 24L shows the end product and the far greater imprecision that came with doing the shaping by hand, including very rough edges, slight off-centering, and unintended bites into the side of the sample. Another issue found during an attempt to do the tensile testing with the Instron was that the samples were too thick to fit within the clamps. Due to time constraints, there was no opportunity to correct the thickness to make the samples usable for tensile testing. The samples were then polished and pivoted to be used purely for hardness testing.

In Figure 24M, the circle highlights several pen marks put on to each of the used samples. The marks were 4 millimeters apart from each other, with the “0 mm” location listed in Tables XII and XIII referring to the very center of the dogbone. As mentioned previously, the shaping was not perfect in symmetry, and the distinction between the base material, HAZ, and weld pool was hard to differentiate visibly post-processing. This is to say that the weld area was not always at this 0 mm point, and based on expected trends, the areas found with the lowest HV values were to be the location of the weld pool.

The base sample, as expected, has very little variation in terms of its hardness, attaining an HV of 101.69 ± 1.704 HV. Then in Table XIV, the weld area was believed to be near the “0 mm” location as it had the lowest HV of 54.31, with values growing higher, the further away. In the aged sample, a similar trend was found more, with the weld pool seemingly being skewed to the right side. The lowest HV recorded for the aged sample was 77.79 at +8 mm from the center, and the highest recorded value was -8 mm from the center at 124.64.

Table XI. Vickers Hardness Testing Data for Base 7005.

Location	D1 (μm)	D2 (μm)	Average D (μm)	Load (gf)	Vickers (HV)	Average HV	STDEV
1	29.87	30.02	29.945	50	103.40	101.69	1.704
2	31.01	29.95	30.48	50	99.80		
3	29.79	30.12	29.955	50	103.33		
4	31.13	29.73	30.43	50	100.13		
5	30.09	30.28	30.185	50	101.76		

Table XII. Vickers Hardness Testing Data for Welded-Untreated 7005.

Location	Distance from Center	D1 (μm)	D2 (μm)	Average D (μm)	Load (gf)	Vickers (HV)
1	-16 mm	29.63	31.66	30.645	50	98.73
2	-12 mm	29.28	31.12	30.2	50	101.66
3	-8 mm	31.66	29.98	30.82	50	97.61
4	-4 mm	34.49	33.86	34.175	50	79.39
5	0 mm	40.64	42	41.32	50	54.31
6	4 mm	35.96	35.86	35.91	50	71.90
7	8 mm	29.57	29.42	29.495	50	106.58
8	12 mm	31.06	31.58	31.32	50	94.52
9	16 mm	32.04	32.27	32.155	50	89.68

Table XIII. Vickers Hardness Testing Data for Welded and Aged 7005.

Location	Distance From Center	D1 (μm)	D2 (μm)	Average D (μm)	Load (gf)	Vickers (HV)
1	-8 mm	27.97	26.58	27.275	50	124.64
2	-4 mm	28.18	28.18	28.18	50	116.76
3	0 mm	28.84	30.01	29.425	50	107.09
4	4 mm	32.03	32.93	32.48	50	87.89
5	8 mm	33.34	35.71	34.525	50	77.79

The HV attained could be correlated via an extrapolation of Lai et al.'s yield stress equation [30]:

$$\sigma_y = K [K(\sigma_0/E + 0.2)^n / E + 0.2]^n \quad (2)$$

where σ_0 represents the stress of the intersection of the plastic flow curved and measured via:

$$\sigma_0 = (K/E^n)^{1/(1-n)} \quad (3)$$

K and n are constants measured based material based constants and recorded Vickers hardness values. The equations for those being:

$$K = A(HV) + B \text{ [MPa]} \quad (4)$$

$$n = C(HV) + D \quad (5)$$

The constants A = 2.093, B = -35.40 MPa, C = -0.0094, and D = 0.721 for aluminum alloys with HV being the recorded Vickers hardness. The equations give the following values based on each sample's recorded hardness values in Tables XIV-XVI.

Table XIV. Estimated Yield Strength of the Base 7005 based on recorded HV.

HV	K (MPa)	n	σ_0 (MPa)	σ_y (MPa)
103.4	181.0	-0.25096	601.5	269.8
99.8	173.5	-0.21712	508.5	245.1
103.33	180.9	-0.250302	599.6	269.3
100.13	174.3	-0.220222	516.6	247.3
101.76	177.6	-0.235544	557.9	258.4

Table XV. Estimated Yield Strength of the Welded-Untreated 7005 based on recorded HV.

HV	K (MPa)	n	σ_0 (MPa)	σ_y (MPa)
98.73	171.2	-0.207062	482.7	238.2
101.66	177.4	-0.234604	555.3	257.7
97.61	168.9	-0.196534	456.6	231.0
79.39	130.8	-0.025266	152.8	136.2
54.31	78.3	0.210486	12.7	55.8
71.9	115.1	0.04514	84.9	107.1
106.58	187.7	-0.280852	691.8	293.3
94.52	162.4	-0.167488	389.4	212.2
89.68	152.3	-0.121992	297.5	185.1

Table XVI. Estimated Yield Strength of the Welded and Aged 7005 based on recorded HV.

HV	K (MPa)	n	σ_0 (MPa)	σ_y (MPa)
124.64	225.5	-0.450616	1352.1	459.3
116.76	209.0	-0.376544	1033.1	379.4
107.09	188.7	-0.285646	707.0	297.2
87.89	148.6	-0.105166	267.6	175.7
77.79	127.4	-0.010226	135.9	129.5

The found yield strength values in Tables XIV and XV are of the same magnitude for the recorded 7005 T4 and T0 properties. The yield strengths also significantly drop off at the weld areas by up to a fourth of the peak recorded values in the base material, as seen in Tables XV and XVI. Notably, the aged welded sample does contain areas with greater than 304.47 MPa estimated yield strength, meeting that specific design requirement. On the other hand, the presumed HAZ and weld pool are significantly under the 304.47 MPa requirement, making them a notable weak point. The samples and the control arms were not first solutionized, which could have allowed for greater uniformity of the dispersed precipitates and thus a greater hardness distribution throughout the products, which decreases the areas containing significantly weaker zones. Another consideration, though, is that the utilized equations may need further material constant adjustment due to the additions of the weld rod, the higher indentation loads, and the heat treatment applied. Greater scrutiny would be required to attain much more specific material constants for these samples. However, the extrapolations would not be needed at all if a standard tensile test was done instead.



Figure 25. (a) Top shows the UCA (painted black) fulfilling all geometric design requirements. (b) Bottom shows the Baja SAE vehicle completing the Oregon competition rock crawl, the most suspension-taxing competition event.

Field testing revealed surviving components, especially during the rock-crawl event pictured in Figure 25b. While it cannot be said that we definitively experienced our maximum load case, surviving components validate our design. A definitive test would test frontal and side

compression impact in a controlled environment (e.g., running the car at 20mph into a wall, or dropping the car on its side). Still, these tests are unfeasible while the car must remain in good condition for competition, meaning these tests should be performed after the competition season.

Future improvements are inspired by the fishbone diagram in Figure 26.

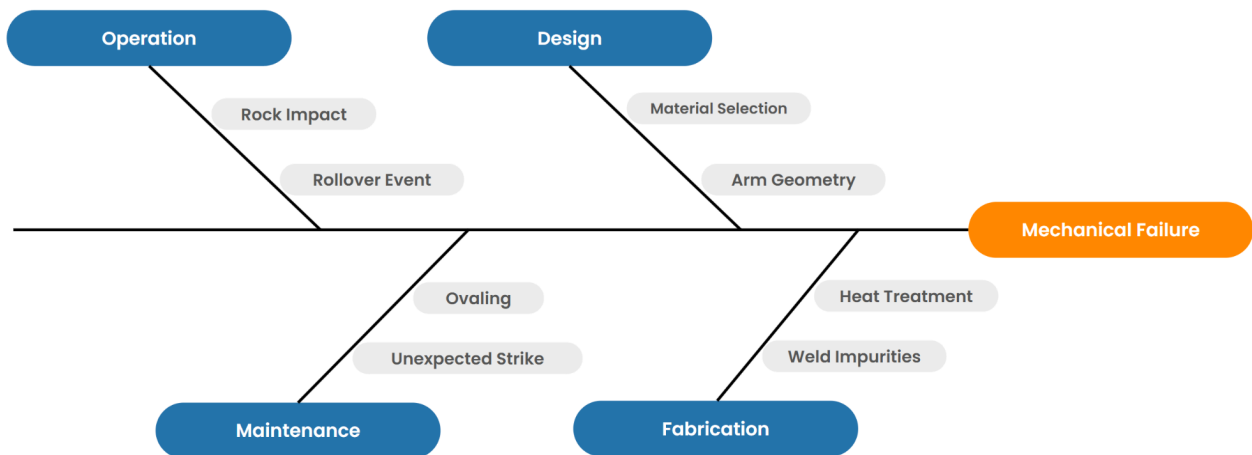


Figure 26. Fishbone diagram displaying primary failure modes

Exploring the different means of failure given the competition and racing context, the *Operation* and *Maintenance* categories are largely uncontrollable. While we can introduce engineering controls to protect our components in storage, this is unfeasible given the busy nature of a student shop. Meanwhile, while operating conditions can be minimized with defensive driving, this is unexpected in a racing environment, and instead designs should account for some driver recklessness. Of course, there is a limit. While the UCA is protected from most rock impacts, a direct rock strike would likely dent or fracture the arm. This is not a failure of the design, but rather an inherent engineering control. While component failure is unwanted, it is useful to protect other members of the subsystem (see Failure Modes and Effects Analysis, not deemed necessary for our subsystem, but an interesting tangent). Similarly, designing for all load cases is an ineffective design approach.

Improvements, then, can be made to the design and fabrication sections. This work validated the material selection and heat treatment components through qualification testing. However, various arm geometries were not explored, and instead a baseline design that met the basic interference and geometric requirements was analyzed. Different geometries can reduce the maximum observed stress, allowing for higher margins of safety. Functionally, this would change the frame analysis performed in Figure 21.

Similarly, while fabrication strategies were noted as an issue, this was dismissed due to the limitations of the student shop. Of course, more steps and measures can be taken to ensure

the highest reasonably possible purity and material cleanliness. Fitup can also be improved by using much finer machining methods.

Still, despite these deficiencies, we were ultimately able to fulfill our design goal. We constructed, using novel AA7005 tempered in-house to T6, a UCA that passed the survivability and geometric requirements.

Conclusions

The objective of this study was to identify a replacement material for the M25 upper control arm that reduces weight relative to the previous 4130 steel design while satisfying the manufacturing constraints of the Baja SAE platform. The section below shows the selected material and its validated performance.

From the screening and ranking process, Al 7005-T6 was identified as the only aluminum candidate that satisfied the density, base-metal yield strength, TIG-weldability, and HAZ retention thresholds. The figure of merit ranked 7005-T6 roughly three to four times above both 4130 normalized and 4130 Q&T, while higher-strength alternatives such as 7075-T6, 2024-T6, 4140 Q&T, and Ti-6Al-4V were excluded because their welded-joint reliability or required process controls were incompatible with the team's TIG fabrication capability. Weldability and HAZ recovery were important factors in the choice of material, as strength-to-weight performance alone is insufficient for selecting a welded structural alloy.

Compositional and microstructural validation was executed using XRF spectroscopy alongside OM, SEM, and EDS. These tests confirmed that the supplied stock met manufacturer specifications for Zn and Mg, the elements driving precipitate formation in the material. The base T4 material exhibited equiaxed grains with micron-scale Fe-Si intermetallics, while the welded-untreated sample showed a banded structure due to dendrite formation. The retention of fine, equiaxed grains in the near-HAZ also indicated that Al_3Zr dispersoids were active in restricting grain growth via Zener pinning. This further supports the selection of 7005 over Cu-bearing 7XXX alloys.

Heat treatment characterization demonstrated that the two-step 93 °C / 160 °C aging procedure successfully advanced the welded material toward a T6 temper, which we observed with precipitate-free zones along grain boundaries and the attenuation of compositional banding observed in the welded-untreated condition.

Redesigning the arm to relocate the shock mount to the lower control arm further reduced the load demands on the upper control arm, allowing the 7005 design to satisfy all geometric constraints while achieving a theoretical mass of 1.154 lb compared to 3.117 lb for the 4130 design (63.4% weight reduction from the M24 4130 control arm design). Finite element analysis under the 2g, 1200 lbf worst-case loading condition produced a minimum factor of safety of 1.02 for the 7005 design compared to 1.67 for 4130. This new control arm

was tested in the field as well, which provided qualitative confirmation that our design met the intended performance target.

Vickers hardness testing across the weld zone confirmed our expected strength gradient, with the lowest hardness values concentrated at the weld pool and partial recovery demonstrated in the aged condition. Although parts of the welded and aged sample surpassed the estimated 304.47 MPa yield threshold, the heat-affected zone (HAZ) and weld pool remained the most vulnerable regions of the assembly. Instead of an issue with the chosen material, the deficiencies resulted due to tool quality in the shop fabrication process, because the only defects that we noticed were in weld porosity or fit-up gaps between materials.

If the design were to be continually improved, future work would be focused on mechanical validation through tensile testing of the bulk, welded-untreated, and welded-treated samples on the Instron to confirm the predicted HAZ strength recovery. Furthermore, the geometry of the entire arm could be optimized through alternative arm profiles, especially one that has more precise fit-ups and a solution treatment step prior to aging, which could reduce peak HAZ stresses. Despite these areas for refinement, the M25 upper control arm demonstrates that Al 7005-T6 is an excellent and weight-efficient replacement for 4130 steel.

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Credits

Abstract - Adam Hernandez, Daphne Nguyen

Background - Adam Hernandez, Daphne Nguyen

Design Requirements - Daphne Nguyen

Screening - Linus Kim

Ranking - Linus Kim, Adam Hernandez

Validation - Arnan Gangla, Richard Liu

Results/Discussion - Daphne Nguyen, Richard Liu, Adam Hernandez

Conclusions - Arnan Gangla