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# Structures Bulletin

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**Subject:** Requirements for Substitution of New Material, Product Form, and Processes for Aircraft Metallic Parts

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**Background:**

The need to replace metallic components on USAF aircraft is increasing as the fleet continues to age, components experience failures, and aircraft near the end of their service lives. The use or proposed use of different materials, product forms, and processes is being driven by a number of factors including, but not limited to, advances in metallurgy and alloy development, the unavailability of legacy alloys and product forms, environmental restrictions, alternative processes and potential cost benefits. Many of the new materials, product forms, and processes present unique challenges when applied to legacy aircraft, and their advantages and disadvantages must be understood to properly exploit them. Of paramount importance is assurance that the proposed materials are well characterized for the intended service environment, usage, and duration. In addition, consideration of all aspects of integrity to include requirements for selection of materials, product forms, and processes stated in the USAF integrity program standards, specifications and guidelines is required.

**Purpose:**

This Structures Bulletin (SB) provides assistance to USAF and industry engineers in selecting material, product form, and/or process substitutions for metallic aircraft parts to minimize the potential for unintended negative consequences. This bulletin and the terminology used in this SB apply across the entire life cycle of USAF systems.

**Scope:**

This SB applies to aircraft materials and processes, aircraft component replacements, aircraft modifications, or aircraft repairs that involve any of the following:

- Material substitution: A change to an aircraft part's material such as class, base, alloy, or heat treatment.
- Product form substitution: A change to an aircraft part's product form such as forging, extrusion, plate, and casting.
- Process substitution: A change to any process used on aircraft parts with the potential to impact structural integrity such as cutting, metal removal, paint removal, and plating & coatings.

**Requirements:**

1. Criticality shall be established for each proposed substitution with consideration for system level effects, such as potential FOD risks to other components if

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substituted material or process fails. In general, there are three broad classifications of criticality considered in this SB that encompass the various terminology used in the standards and specifications for aircraft structures, mechanical subsystems, and propulsion integrity programs. These are:

- Critical. Failure of aircraft part may lead to loss of aircraft, loss of stores, inability to release stores, abortion of mission, or endanger personnel. Terms such as Safety-of-Flight, Critical Safety Item, Fracture Critical, and Mission Critical are associated with this classification.
  - Semi-critical. Failure of aircraft part may reduce system efficiency, but does not lead to loss of aircraft or endanger personnel. Terms such as Durability Critical and Maintenance Critical are associated with this classification.
  - Non-critical. Failure of component or repair is contained and will not affect other system elements or pose a danger to personnel. Terms such as Durability Non-Critical, Normal Controls are associated with this classification.
2. USAF and industry engineers shall employ the tables and specific considerations in this SB when considering material, product form, and/or process substitutions.
  3. Mechanical property impacts shall be considered for material, product form and process substitutions. Guidance for generating statistically significant properties can be found in Appendix 1. A selection of mechanical property data sources are shown in the reference section [1-4]
  4. Potential substitutions with Technology Readiness Level (TRL) or Manufacturing Readiness Levels (MRL) at a level of 5 or below shall be considered “high” risk independent of what is listed in the tables [5,6].
  5. AFRL/RX shall be consulted on potential substitutions characterized as “high” risk as identified in Tables 1 through 3 or by low TRL or MRL. AFRL/RX shall be consulted on potential material, product form, or process substitutions to aircraft metallic parts that are not addressed by this SB. AFRL/RX should be consulted for “low” and “moderate” risk substitutions.
  6. Material, product form, and process substitution decisions shall take nondestructive inspection/evaluation (NDI/E) requirements into account. The efficacy of these inspections must be validated either through the use of industry standard practices (e.g. SAE or ASTM) applicable to the material or product form or by demonstration. Demonstration must include empirical evidence that inspection processes detect required damage types, sizes, and orientations to

the reliability requirements established in the appropriate USAF integrity program.

7. Material, product form, and process substitution decisions shall account for locations at which substitutes interface with existing components [7,8]. Appropriate coatings and/or sealants must be considered for these locations to minimize potential risks of corrosion and wear [9,10]. Other interface-related issues such as thermal expansion coefficients, current and grounding paths (e.g., lightning strike protection), stiffness, etc. must be considered.
8. Appropriate risk mitigation actions shall be planned and executed for all substitutions [11-16]. These actions include, but are not limited to, development tests, certification analyses, first article tests, reevaluation of inspection intervals or methods, strength or life analyses, etc.
9. The appropriate USAF integrity program Master Plan (or corresponding document) shall be used to document the requirements, decision making process, and the risk mitigation actions taken for all substitutions.
10. "Risk" as used in this SB should not be equated to system safety risk in MIL-STD-882. "Risk" in this SB is a qualitative assessment of the complexity of making a material, product form, and/or process substitution; or of the potential adverse technical and/or programmatic impacts of such a substitution.

**Material Substitution Table:**

Table 1 illustrates, qualitatively, the relative complexity and technical/programmatic risk associated with potential material substitutions for a range of part types.

Table 1 Material Substitutions - Complexities and Risks

Substitution Type▶  Part Class. ▼▼	Same Alloy Group, Same Heat Treatment (e.g., 7XXX-TXYZ Al for 7ABC-TXYZ Al)	Same Alloy Group, Different Heat Treatment* (e.g., 7XXX-TXYZ Al for 7XXX-TABC Al)	Different Alloy, Same Base (e.g., 2XXX Al for 7XXX Al)	Different Base (e.g., Al for Ti)	Different Class (e.g., Composite for Metal)	Hybrid Material (e.g., Metal-Composite Laminate for Metal)
<b>Critical</b>	<b>L</b>	<b>M</b>	<b>H</b>	<b>H</b>	<b>H</b>	<b>H</b>
<b>Semi-Critical</b>	<b>N</b>	<b>L</b>	<b>M</b>	<b>M</b>	<b>M</b>	<b>H</b>
<b>Non-Critical</b>	<b>N</b>	<b>N</b>	<b>L</b>	<b>L</b>	<b>M</b>	<b>M</b>
<b>KEY</b>	<b>Complexity / Risk</b>					
<b>N</b>	Negligible					
<b>L</b>	Low					
<b>M</b>	Moderate					
<b>H</b>	High					

\* Substituting T7 for T6 heat treatments is encouraged when the application can accommodate the reduction in mechanical properties.

Details on substituted materials can be found in Appendix 2.

**Product Form Substitution Table:**

Table 2 illustrates qualitatively, the relative complexity and technical/programmatic risk associated with potential product form substitutions. Although, welded and built-up structures are not product forms, they are included in this table to reflect recent manufacturing trends toward unitization and monolithic alternatives.

Table 2 Product Form Substitutions - Complexities and Risks

Replacing ► ▼With ▼	Forging	Extrusion	Machined Plate	Casting	Welded Structure	Built-Up Structure
Forging	N	N	N	N	N	L
Extrusion	L	N	N	L	N	L
Machined Plate	M	M	N	L	L	L
Casting	H	H	H	N	L	M
Welded Structure	H	H	H	M	N	M
Built-Up Structure	M	M	M	M	L	N
Additive Mfg.*	H	H	H	H	H	H
<b>KEY</b>	<b>Complexity / Risk</b>					
<b>N</b>	Negligible					
<b>L</b>	Low					
<b>M</b>	Moderate					
<b>H</b>	High					

\* Additive Manufacturing includes, but is not limited to, laser additive manufacturing, electron beam additive manufacturing, cold spray processes, etc.

Details on substituted product forms can be found in Appendix 3.

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**Process Substitution Table:**

Table 3 illustrates qualitatively, the relative complexity and technical/programmatic risk associated with potential process substitutions.

Table 3 Process Substitutions - Complexities and Risks

Replacing ► ▼With▼	Metal Cutting Processes	Metal Removal Processes	Paint Removal	Plating & Coating	Heat Treating	Engineered Residual Stresses	Joining Methods	Proprietary Processes
Alternative Methods*	H	H	H	H	H	H	H	H
<b>KEY</b>	<b><i>Complexity / Risk</i></b>							
<b>N</b>	Negligible							
<b>L</b>	Low							
<b>M</b>	Moderate							
<b>H</b>	High							

\* Alternative Methods include processes such as laser cutting, water jet cutting, mechanical paint removal (e.g., abrasive media blast), thermal paint removal (e.g., laser, flashlamp), cold/thermal/plasma spray, and alternative plating processes.

Details on substituted processes can be found in Appendix 4.



**Summary:**

USAF and industry engineers shall to use this Structures Bulletin when making material, product form, and/or process changes to aircraft metallic parts. USAF and industry engineers shall consult with AFRL/RX on potential substitutions characterized as “high” risk and are encouraged to do so for “low” and “moderate” risk substitutions. AFRL/RX contact information is:

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## **APPENDIX 1**

### Guidance for Material Property Data Generation

## **Generation of Material Property Data for Material Changes**

Before beginning property data generation, adequate specifications must be available for the process or material. These specifications shall be approved by the Cognizant Engineering Organization (CEO) as sufficient for the application.

Statistically significant material property data are required as part of Lincoln's five pillars [13]. In many instances access to the original engineering data and analysis methods is not available. In these cases, the following process for static and fatigue initiation (stress-life) properties is recommended.

Static and physical property data (i.e., tensile, bearing, compression and shear) must exist for new material, product forms or processes. The procedure for static and physical property data generation is clearly spelled out in chapter 9 of MMPDS [3] (Table 9.2.4) and shall be followed. For Semi-Critical and Critical applications, A-basis or B-basis data are required, as determined by the CEO. S-basis may be considered for Non-Critical applications. Any debits must be assessed against original design and load case requirements. Material property data not required by the application, as determined by the CEO, do not have to be generated.

Supplemental properties addressed in MMPDS (fracture toughness, creep, effect of temperature) may be required for the application. This determination is made by the CEO. MMPDS provides the required statistical basis for the properties.

For properties not found in MMPDS that are required for the application (e.g., threshold stress intensity factor for stress corrosion cracking,  $K_{ISCC}$ ), commercially available specifications should be used.

### **Fatigue Data:**

#### *Initiation*

The processes for generating statistically significant fatigue crack initiation and fatigue crack growth property data are not sufficiently described in MMPDS. Fatigue performance of substitute materials and processes shall be assessed in order to determine impacts of the substitution. Potential impacts include more frequent maintenance, increased life cycle cost, or an increased propensity for failure. The recommended process for fatigue data generation and analysis is as follows.

For fatigue crack initiation, nine valid tests for each of three separate stress levels covering the expected usage range shall be completed. The process shall be repeated for two stress ratios (R). The total number of tests is 54, nine at each of six stress level

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and stress ratio (SR) combinations. Valid tests means that specimens fail in the gage section and are not influenced by errors in test method or specimen preparation. Nine tests at each condition is required to ensure that a representative median of the data is established [17].

The data shall be analyzed using the two parameter Weibull distribution (maximum likelihood estimation) and compared to baseline material two parameter Weibull analyses [18]. The analysis method shall be the same for both the baseline and proposed substitute material or process. Calculate the values for mean and 90% reliability (R90), both from the Weibull distribution, for every set of data at each SR combination. Compare the mean and R90 values of the proposed substitute material or process to the baseline values at the same SR conditions. The proposed substitute material or process values must be greater than 80% of baseline values at 5 of the 6 SR combinations in order to assume no fatigue debit. If more than 6 SR combinations are tested, only one exception is allowed (e.g., 7 of 8, 11 of 12, etc.)

If testing nine specimens at each SR combination is impractical, a minimum of five specimens may be used. Use of five specimens significantly decreases the likelihood of meeting the acceptance criteria.

If the substituted material fails to meet the criteria after nine specimens are tested at each SR condition, additional specimens, up to 12, may be tested. Additional data has been shown to increase the fidelity of the comparison. The relative improvement in the comparison is small above 12 specimens per SR condition.

### *Fatigue Initiation Example*

Assume two materials are considered as proposed substitutes for a baseline. All materials have nine fatigue initiation test data points at stress levels of 80, 90 and 100 ksi maximum stress, and stress ratios of  $R=0.1$  and  $R=-1$ . This represents the six SR combinations required as described above. The notional fatigue data for 100 ksi,  $R=0.1$  is shown in Table A1.1.

Table A1.1. Cycles to Failure at 100ksi,  $R=0.1$

Baseline	Substitute 1	Substitute 2
12772	11491	9937
13870	13695	11893
15620	14220	13756
16320	18448	15777
21520	19467	16089
23090	20781	20425
24034	22700	21084
25610	25610	29407
25894	25753	30991

The mean of the data is directly calculated by taking the average of the values. The data should use statistical software, such as JMP Weibull++, to determine the Weibull shape and scale parameters. Once the Weibull shape and scale are determined, the R90 value can be calculated. The Weibull fits and the calculated means are shown in Figure A1.1 for the SR combination of 100ksi,  $R=0.1$ .

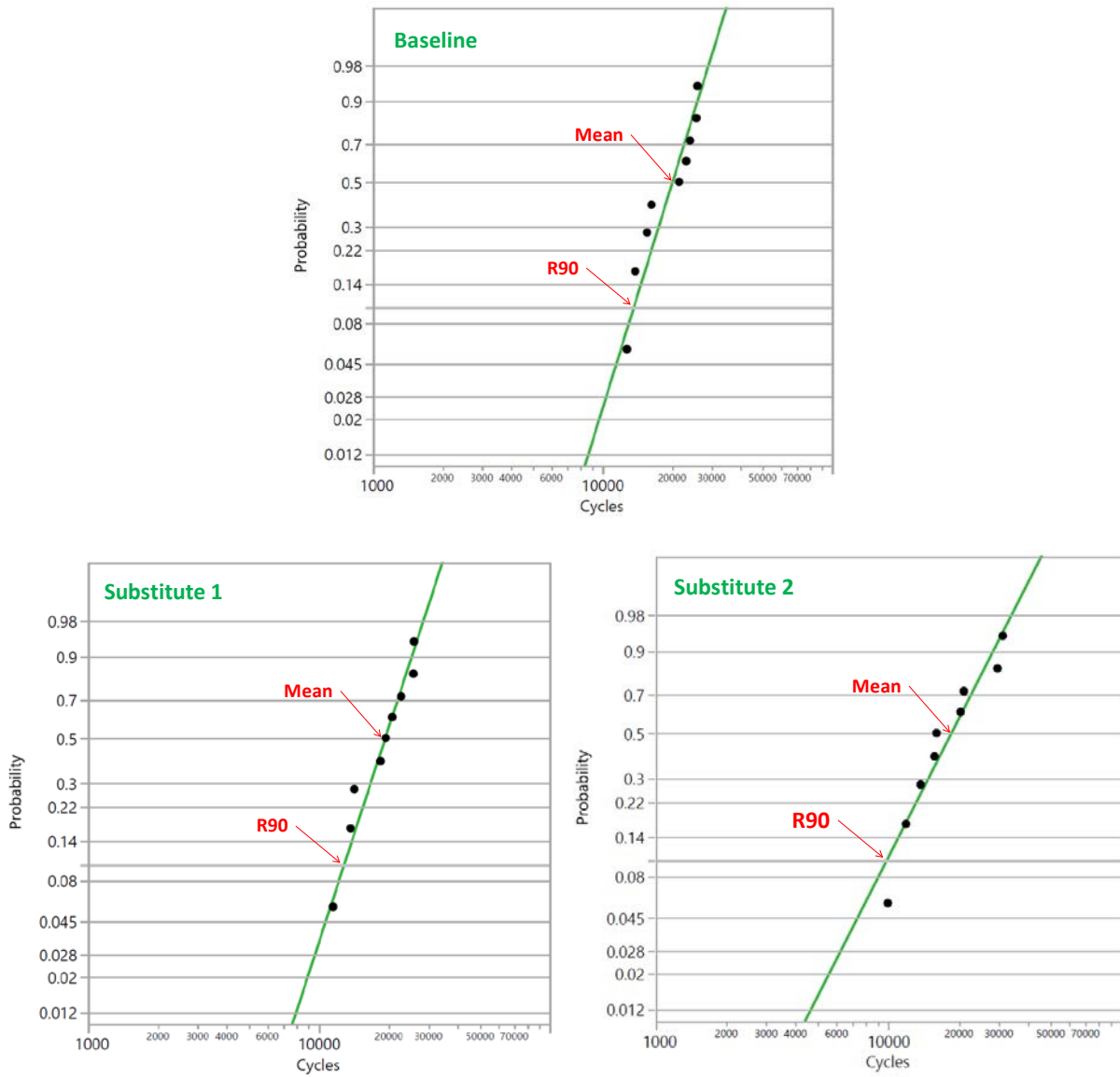


Figure A1.1. Weibull plots for SR combination of 100 ksi, R=0.1.

For this SR combination, the mean and the R90 are compared to 80% of the values for the baseline. This is shown in Table A1.2.

Table A1.2. Material Acceptance Evaluation

0.8 Baseline	Substitute 1	Substitute 2
Mean = 15962	Mean = 19129	Mean = 18818
R90 = 10915	R90 = 12832	R90 = 9789

In this case, both the mean and R90 for potential substitute 1 meet the acceptance criteria. The R90 value for potential substitute 2 falls below the acceptance criteria, so the material fails the comparison at this SR combination. If comparisons at a minimum of 5 of 6 SR combinations meet the acceptance criteria, the material is considered an acceptable substitute.

For clarity, an example evaluation is shown in Figure A1.2. In this example, potential substitute 1 is considered an acceptable substitute because more than 5 of 6 SR combinations pass the criteria (All 6 pass in this case). Potential substitute 2 is not acceptable because only 4 of 6 SR combinations pass.

Stress	R	SR Comb.	Baseline		Baseline x 0.8		Substitute 1		Substitute 2		
			Mean	R90	Mean	R90	Mean	R90	Mean	R90	
100	0.1	1	19952	13644	15962	10915	19129	12832	18817	9789	
100	-1	2	12909	8700	10327	6960	15113	8582	17213	8220	
90	0.1	3	106358	76986	85086	61588	84111	44047	68017	52159	
90	-1	4	92848	65342	74278	52273	96944	73216	98500	62372	
80	0.1	5	594434	244184	475547	195347	611722	226064	636222	302494	
80	-1	6	545841	230984	436673	184787	514556	295561	668889	280227	
								Result: <i>PASS</i>		Result: <i>FAIL</i>	

Figure A1.2. Example evaluation for two materials compared to a known baseline. Green boxes represent values that are greater than 80% of the baseline value. In this case, Substitute 1 is acceptable because 5 of 6 SR pairs meet the criteria. Substitute 2 is not acceptable because only 4 of 6 SR pairs pass. Yellow boxes show the failed SR pairs for Substitute 2.

### *Crack Growth*

For applications that require linear elastic fracture mechanics (LEFM) analysis methods to determine equivalence, fatigue crack growth data ( $da/dN$ ) shall be developed using ASTM E647 [19] testing specification. A minimum of 3 replicates per condition (stress ratio, temperature, etc.) shall be tested. For material with fleet experience, a mean curve may be established from these data and used in damage tolerance comparisons. For materials without significant fleet experience, an upper bound curve (i.e., fastest crack growth) shall be established from the data.



## **APPENDIX 2**

### Guidance for Material Substitutions

## **2.0 Specific Material Substitutions with Negligible Risk**

Materials with obsolete specifications can be replaced by materials with superseding specifications as long as they are approved by AFLCMC/EZSS. Superseding specifications approved by AFLCMC/EZSS have already been determined to be technically equivalent. For example, mill annealed Ti-6-4 bar per MIL-T-9047 [20] may be replaced with AMS6931 [21]. For obsolete specifications with no clear supersession and that haven't been approved by AFLCMC/EZSS, contact AFRL/RX

For aluminum alloys, the -T7 temper is an acceptable substitution for the -T6 temper if the reduced strength is sufficient for the application. Stress relieved tempers, -TXX51 or -TXX52, are acceptable substitutes for base tempers. For example 7075-T7351 may be substituted for 7075-T73. Finally, the -T42 temper may be substituted for -T4 and the -T62 temper may be substituted for -T6.

For precipitation hardened steels, final aged condition material may be substituted for material provided in the solution treated condition and subsequently aged to the final condition. For example if 15-5PH is supposed to be procured in the solution treated condition per AMS5659 [22] and subsequently aged to the H1025 condition, 15-5PH H1025 per AMS5659/H1025 may be procured instead. Additionally, substituting 15-5PH for 17-4PH in the same H condition is acceptable.

### **2.1. Same Alloy Group, Same Heat Treatment**

For example, 7075-T6 for 7050-T6, Mill Annealed Ti-6-4 for Mill Annealed Ti-6-2-4-6, 13-8PH H1025 for 17-4PH H1025.

#### **2.1.1. Rationale for Risk**

These type of substitutions are more likely to pose sustainability impacts than safety of flight impacts. Differences in corrosion and inherent defect types must be considered. In rare cases, there may be new failure mechanisms that could affect safety of flight.

#### **2.1.2. Applications Evaluated**

Exhaust washed structures have substituted Ti-6-2-4-2 duplex annealed for Ti-6-4 in the same condition. The higher temperature properties of Ti-6-2-4-2 resulted in longer lives, but reduced repairability.

### 2.1.3. Ongoing Evaluations

Aluminum Alloy 7085 is being considered for a large number of 7xxx material replacements. The fracture behavior of thick section 7085 remains a concern due to reports of unusual crack growth behavior. This behavior is currently under evaluation by AFRL.

## 2.2. Same Alloy Group, Different Heat Treatment

For example, 7075-T7 for 7075-T6, Solution Treated Ti-6-4 for Mill Annealed Ti-6-4 or 17-4PH H1100 for 17-4PH H1025.

### 2.2.1. Rationale for Risk

Changes in heat treatment may negatively affect safety of flight in critical applications. Examples include decreased fracture toughness in solution treated titanium, susceptibility to stress corrosion cracking in precipitation hardened (PH) steels and aluminum alloys.

### 2.2.2. Applications Evaluated

Multiple 7xxx-T6 parts have been evaluated for substitution with 7xxx-T7. This substitution is recommended for eliminating the possibility of stress corrosion cracking if the application can handle the reduction in static and fatigue properties.

## 2.3. Different Alloy, Same Base

For example, aluminum alloy 2024 for 7075, Ti-15-3-3-3 for Ti-6-4 or 13-8PH for 4130 steel.

For reference, aluminum alloys are identified by a four digit designator. A different first number represents a different alloy system.

This is similar to iron base alloys, where a different first number represents a different alloy, but the designator convention is not standardized for iron base alloys. Iron base can have three and four digit designators which represent different alloys, and some alpha numeric combinations. If in doubt, assume the designator represents a different alloy.

Titanium alloys can be roughly grouped into commercially pure (CP), alpha, alpha-beta and beta. Specific alloys in these groups can be found in AMS-T-9047 [23].

Nickel alloys are frequently described by trade names which makes determination of different alloy or alloy group difficult. Assume different nickel designators represent a different alloy.

### 2.3.1 Rationale for Risk

Some material substitutions in this class can result in significant impacts to flight safety. For example, substituting a high strength steel for a PH steel will lead to extreme differences in corrosion response. This would require additional coating systems and different processing methods. Similarly, substituting Ti-8-1-1 for Ti-6-4 would result in a high potential for embrittlement, where none had previously existed.

### 2.3.2. Applications Evaluated

Per AWB-1015 [24], change evaluation teams have assessed two substitutions in this class.

7075-T7451 was substituted for 2014-T6 in the C-130J Elevator Crank and Collar. The use of 7xxx series ensured the part met design strength and fatigue requirements, while the use of the –T7 temper reduced the susceptibility to stress corrosion cracking.

15-5PH was substituted for 4130 in the C-130J nose landing gear drag brace fitting. While there was a debit in mechanical properties, the 15-5PH still had sufficient properties to meet design requirements. The use of 15-5PH eliminated a corrosion concern on the 4130 part.

## 2.4. Different Alloy Base

For example, substituting titanium for aluminum.

### 2.4.1. Rationale for Risk

Material substitutions in this class can result in significant impacts to flight safety and likely require different coatings, processing and attention to interface issues. The failure mechanisms for different alloy bases can be completely different. For example, alpha case formation in titanium is a significant concern, but this does not exist in iron or aluminum base alloys.

### 2.4.2. Applications Evaluated

AWB-1015 change evaluation teams have evaluated one substitution in this class

4130 steel was substituted for 7075-T6 in the C-130J nose landing gear drag brace. The substitution greatly reduced the susceptibility of the part to stress corrosion

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cracking. Different corrosion protection measures were needed for the 4130 part, but it provided significant improvement in strength and fatigue resistance.

## **2.5. Different class of materials**

For example, substituting a composite for a metal.

### **2.5.1. Rationale for Risk**

Safety of Flight components typically have a wide range of criteria that they must meet. These include structural integrity, survivability, inspectability, maintainability and other specific design requirements. Typically, there are gaps in the technical data with different classes of materials that lead to unintended consequences.

## **2.6. Hybrid Materials**

For example, substituting GLARE for aluminum.

### **2.6.1 Rationale for Risk**

Similar to different classes of material, gaps in technical data with hybrid materials can lead to unintended consequences. This risk is compounded by less experience with, fewer accepted specifications for, and generally less data supporting hybrid materials when compared to many composites.

### **2.6.2. Applications Evaluated**

A-10 program office evaluated an application of fiber metal laminate substitution for aluminum alloy 2024-T351 plate. The substitution was not implemented because data and analysis generated by the program office indicated the substitution did not provide the expected benefit. Potential issues concerning graphite contamination on the shop floor and stiffness changes driving different failure modes were also noted.

## **APPENDIX 3**

### Guidance for Product Form Substitutions

### **3.0. Product Form Substitutions with Negligible Risk.**

Size substitutions are acceptable given the product form does not change and the substituted size is within the same group on the controlling specification. Specifications typically control thickness, although they may control other size parameters as well. For example, AMS6931 has two thickness groups, up to 4.00 inch and 4.00 to 6.00 inch. Additionally, AMS6931 requires the maximum cross sectional area at time of final thermomechanical processing to be less than 48 in<sup>2</sup>. If a drawing requires AMS6931 bar 2.50 inch thick x 5.00 inch wide, larger sizes such as 3.50 inch thick by 7.00 inch wide bar may be substituted (note, thickness is controlled and width is not). However, neither a 3.50 inch thick by 15.00 inch wide bar (violates the 48in<sup>2</sup> max) nor a 4.50 inch thick bar (different thickness group) would be acceptable substitutes. Thickness substitutions are not applicable if stock thickness limits are listed on the engineering drawing.

For sheet, strip, plate, bar, rod, extrusion, tubing and hand forged product forms, any smaller size, either thickness or cross-sectional area that will permit production of the final part is an acceptable substitute.

For sheet and plate, width substitutions without restriction are acceptable.

Length substitutions for stock product form are acceptable as long as the final component can be produced from the substituted length.

Different stock surface conditions on steel bar and rod are acceptable as long as surfaces will be removed in downstream manufacturing operations. A minimum of 0.045" of material must be removed to ensure decarburized layer is eliminated.

### **3.1. Substituting Forgings**

#### **3.1.1. Rationale for Risk**

Forgings are a high quality product form. If the thickness of the substituted forging differs from the original, mechanical properties changes may result. Specific issues have been noted when replacing built-up structure with forgings. The depth of some of the areas of these components has resulted in fatigue issues while machining the forging to final shape. Consideration must also be given to differences in residual stress state when changing product form.

### 3.1.2. Applications Evaluated

Single piece hand forgings were used to replace the built-up crew emergency escape door on the C-17. Machining the forgings resulted in fatigue crack initiation due to sub-optimal machine paths. These issues were corrected by changing the machine tool path after several parts had cracked in production.

Die forged titanium main spars on a B-2 were replaced using hand forgings to repair thermal damage. The hand forgings were significantly thicker than the original die forging. Mechanical testing was required to determine the debit in mechanical properties, but once data were available the substitution was approved.

## 3.2. Substituting Extrusions

### 3.2.1. Rationale for Risk

Extrusions are a high quality wrought product form. The production of this material tends to result in a significant amount of microstructural anisotropy. Machining the extrusions also has the potential to expose end grains, leading to corrosion issues where none had previously existed. Anisotropy and corrosion prevention must be considered when substituting extrusions. Machining operations will require inspections that may not have previously been required. For example, penetrant inspections may be required on machined surfaces that were previously in the as-forged condition.

Care must be taken to ensure that loads are not applied in directions that would adversely affect component integrity. The ST direction typically has the worst mechanical and corrosion properties.

Consideration must also be given to differences in residual stress state, the effect of machining on surface integrity and the geometry of any machined features.

## 3.3. Substituting Machined Plate

### 3.3.1. Rationale for Risk

Machined plate substitutions have to account for microstructural anisotropy, exposed end grains and may have less wrought refinement than extrusions or forgings. The lower amount of mechanical work during processing leads to a higher degree of variability in mechanical properties. Machining operations will require inspections that may not have previously been required, see 3.2.1.

Care must be taken to ensure that loads are not applied in directions that would adversely affect component integrity. Substituted materials likely have anisotropic

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material properties and may demonstrate inferior capabilities, including damage tolerance, in certain orientations. For example, if plate is used in the substitution, the risk of failure due to out-of-plane loading should be mitigated since the short transverse (S-T) direction typically has lower fracture toughness and crack propagation resistance than the long transverse (L-T) or longitudinal (S-L) directions.

Consideration must also be given to differences in residual stress state, the effect of machining on surface integrity and the geometry of any machined features.

### 3.3.2. Applications Evaluated

Aluminum aileron control linkage forgings on T-38s were replaced with machined plate as they reached their end of life. Issues arose because the coatings were required to protect the machined parts from exposed end grain corrosion and the machining process necessitated fluorescent penetrant inspection. Parts were coated before inspection, requiring significant rework in order to inspect properly and ensure part integrity.

## 3.4. Substituting Castings

### 3.4.1. Rationale for Risk

When castings are considered as substitutes for other product forms, casting factors, and initial damage assumptions (especially for durability and damage tolerance applications) must account for inherent material defects specific to castings such as shell defects, hard-alpha contamination, shrink, porosity, weld defects, grain size, hot tears, incomplete densifications, prior particle boundaries, etc. Castings have higher variability in mechanical properties than wrought materials due to widespread defect distribution. Static variability is discussed in JSSG-2006, but variability of secondary properties such as crack growth must be determined on a component by component basis. Reference [25] may be consulted when titanium castings are being considered as substitutes for other product forms.

## 3.5. Substituting Welded Structure

### 3.5.1. Rationale for Risk

When welded structure is considered as a substitute for other product forms, component design and initial crack size assumptions (especially for durability and damage tolerance applications) must properly account for process-dependent defects specific to weldments such as lack of fusion, inclusions, arc damage, burn through, warping, residual stresses, etc. Welds should be located in non-critical areas with considerations such as fabricability, maintainability and inspectability taken into account.

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Full heat treatment after welding is highly recommended. Approved aerospace welding specifications, such as [26-28], shall be used, and mechanical and physical properties must be determined and documented in the Procedure Qualification Record using the component's production weld processes. Fastener holes should not be made through the welds.

### **3.6. Substituting Built-Up Structure**

3.6.1. Built-up structures introduce multi-material interfaces to formerly monolithic parts. Corrosion must be prevented on faying surfaces and crevice corrosion potential greatly increases. Additionally, most built-up structure are assemblies of very thin plate or sheet material. Thinner materials are likely to have higher static properties, but higher degrees of anisotropy and may suffer significant mechanical property debits in lower-strength directions.

Built-up structure also requires a significant amount of hole drilling and edge cutting. This exposes the part to potential failures from poorly prepared cut surfaces.

Built-up structures are typically not preferred substitutes for monolithic structures and should only be used after serious consideration.

### **3.7. Substituting Additive Manufacturing**

#### **3.7.1. Rationale for Risk**

Metallic Additive Manufacturing (AM) is a process to make objects from 3D model data, usually layer upon layer, typically with the application of a heat source to melt metal affluent in the form of a powder, wire or foil. There are currently no industry accepted AM process specifications or agreement upon quality assurance provisions.

Inherently, metallic AM is a welding process and this fact must control the qualification/certification methodologies. Metallic AM parts will have different microstructure, properties, and nondestructive inspection issues than the same shaped wrought (forgings, plate, extrusions, etc.) or cast products.

AFRL has been involved with AM since 2000. In that time, four consistent issues have repeatedly surfaced with proposed uses of AM. These issues are:

- A. Demonstrated Process Control
- B. Established, Statistically-Based Physical and Mechanical Properties
- C. Validated Non-Destructive Evaluation & Quality Assurance
- D. Defined Post-Processing & Residual Stress Management

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#### 3.7.1.1. Demonstrated Process Control

Conventional processes such as forging and casting have somewhere between 20 and 50 essential process parameters. AM can have as many as 200 essential process variables, which makes process control significantly more difficult. Some of the most critical variables are component thickness, build geometry, the component provider and the component designer, but this is just a small subset of the 200 possible variables.

Demonstrated process control must include verification that the producer has identified all of the essential process variables for their process and does not allow them to change without approval of the CEO.

#### 3.7.1.2. Established, Statistically-Based Physical and Mechanical Properties

Mechanical properties must be established from specimens produced using the final production build process. It is important that these test specimens have been exposed to all of the manufacturing processes that the production part will experience including post deposit thermal treatments, machining, HIP, inspection, and etching.

#### 3.7.1.3. Validated Non-Destructive Evaluation & Quality Assurance

The Quality Assurance (QA) plan must consider both volumetric and surface inspection procedures. Due to the nature of the welding-like process, volumetric inspection must be performed on all critical and semi-critical parts produced via AM.

The NDE procedure must be able to detect flaws of a critical size. Validated probability of detection (POD) curves must be generated to support inspection of critical and semi-critical AM parts. The inspection plan must be approved by the CEO.

Efforts to evaluate AM deposits using typical nondestructive testing methods have revealed significant inadequacies to identify the presence of critical flaws, Figure A3.1.

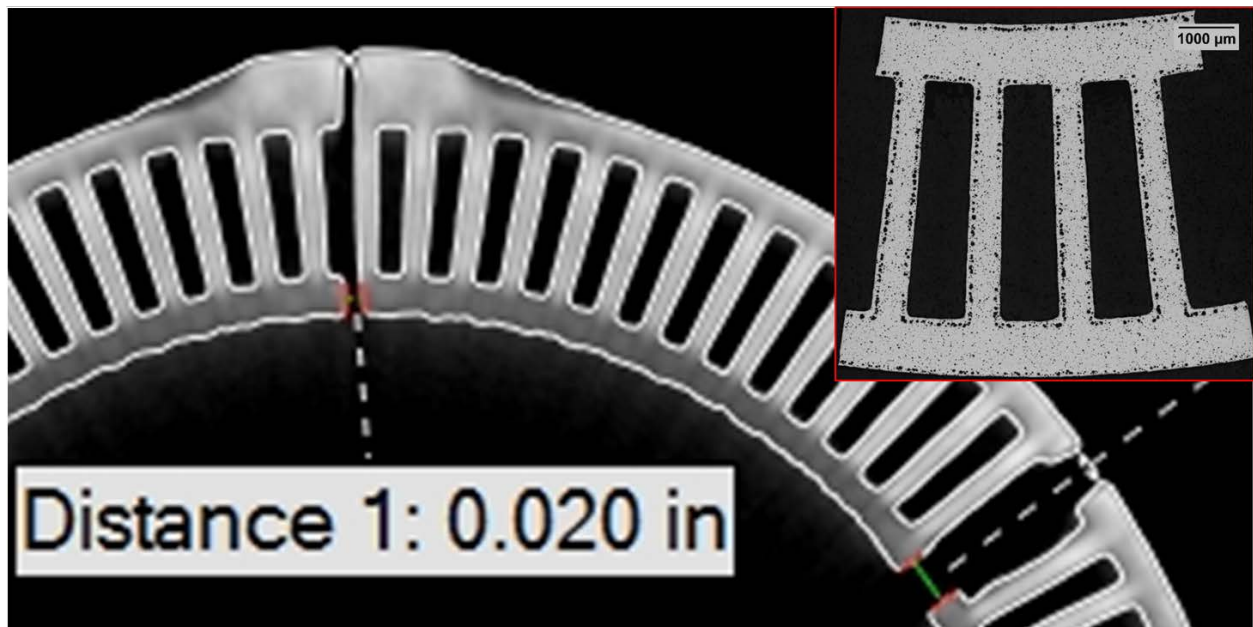


Figure A3.1. Comparison of high resolution computed tomography results and destructive metallurgical evaluation in red outlined box showing NDE shortcomings. CT showed no indications but destructive analysis showed widespread, aligned porosity.

#### 3.7.1.4. Defined Post-Processing & Residual Stress Management

As a result of the fast cooling rates and the complex thermal history of deposits, high residual stress is a consequence of AM. Stress relief is most often obtained by thermal treatments, either during or after the part build. In addition to stress relief, some materials will require a post deposit thermal treatment, such as aging, to obtain optimal properties. Finally, non-thermal post processing such as machining is often required to address surface finish and dimensional requirements.

The effect of these treatments on inspection, corrosion and mechanical properties must be determined and be included in cost models and lifing analysis.

#### 3.7.2. Applications Evaluated

F-15 fracture critical aluminum pylon ribs were substituted using AM Ti-6-4 in response to a supply issue. The increased strength of the Ti-6-4 material helped to reduce the risk of the substitution. The additional quality assurance provision required by AM increased the cost of the part to approximately 3x greater than the aluminum part. Production was halted after approximately 15 component were fabricated.

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### 3.7.3. Ongoing Evaluations

A recent study at Oak Ridge National Laboratory examined the effect of processing parameters in AM. They found several instances where changing just one of the essential process variables (cooling rate) changed the mechanical property response in a nickel alloy, IN 718. The strength increased from 137 KSI to 160 KSI, but the elongation decreased from 34% to 22% and the modulus decreased from 22 *MSI* to 2.17 *MSI*. Elongation as low as 6% was seen simply by changing build orientation.

If a USAF engineer is considering AM substitutions, the list of factors below has been developed based on lessons learned and knowledge of the unique attributes of the AM processes. These factors may be utilized as a guide for the type of data required to initiate materials substitution or materials qualification discussions with AFRL/RX. These factors merely provide a guide for point-of-entry discussions and are not intended to be fully exhaustive.

#### Component Design Requirements:

Part Classification (e.g., critical, semi-critical, non-critical)

Economic impact and life cycle costs

Materials Substitution (are you changing the material system? From what to what?)

Extent of available technical data for the component's requirements

Accessibility of the component while on aircraft

Proposed certification methodology with component conformance plan

#### Component Geometry Requirements:

Part size (total envelope and volume)

Part complexity (surface area-volume ratio, fraction envelope solid, symmetry)

Dimensional conformance requirements

Surface Finish requirements

#### Established and Demonstrated Process Control:

Feedstock vendor experience

Feedstock control specification

Essential process parameters

Process control/monitoring methodologies

Process specification (such as AWS D20.1 [29] or AMS7000 [30] and AMS7003 [31])

Post-AM processing plan, heat treatment condition, repair and straightening allowances

Process control documentation for post-AM processes (heat treatment, machining, etc.)

AM vendor experience of similar hardware (material, size, complexity)

Consistent build geometry for entire volume

Different vendor

### Material Integrity and Quality Assurance:

Feedstock control inspection requirements

Maturity of mechanical property databases for primary and secondary properties

Applicability/experience of mechanical property database to part geometry and material

Maximum allowable flaw size according to design requirements

Post-manufacturing surface and volumetric inspection requirements

Demonstrated/validated inspection process and inspection plan

Destructive evaluation plan

Experience with process- and material-specific effect of defects

Chemical composition

## **3.8. Substituting Cold Spray**

### 3.8.1. Rationale for Risk

Cold spray is a process that has a large number of essential process variables (a variable that affects mechanical properties) relative to traditional processing. The sensitivity of material properties to these variables is not well understood.

### 3.8.2. Applications Evaluated

An AFLCMC Rapid Innovation Fund program was initiated in 2014 to evaluate the potential applications of cold spray to repair or modify existing components. Potential applications included B-1 Forward Equipment Bay (FEB) door hole restoration, F-15 Aircraft Mounted Accessory Drive gear box restoration, F-16 Accessory Drive Gearbox, F-16 Air Inlet Housing flowpath restoration and B-1 hydraulic tube chafe protection.

The B-1 FEB door repair for 0.030" oversized holes was approved in late 2017 by an AWB-1015 change evaluation team. Significant time and effort were required to establish process control documents, generate applicable test data and develop quality control criteria. The F-16 Air Inlet Housing was abandoned due to resource constraints.

### 3.8.3. Ongoing Evaluations.

Any potential application must have the entire range of process parameters qualified (including tolerance ranges) and a fixed process approved by the CEO. Any change in these parameters or expansion of allowable parameter tolerance must be re-qualified. Controls must be established and validated to ensure essential process variables are maintained within the qualified range.

MIL-STD-3021 [32] is the DoD standard for cold spray processes. While MIL-STD-3021 covers the process of cold spray application, it does not provide adequate quality control for specific applications. Recommended quality control acceptance criteria are shown in Table A3.1. based on application criticality.

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1. Coating restoration (Non-Critical). Cold spray is used to replace worn anodize layers, cladding or other coating systems. Cold spray has been proven not to damage the substrate or have a negative impact to the system if it fails.
2. Non-structural dimensional restoration (Non-Critical). Used to restore worn holes or mating surfaces to original dimensions. It must be proven that application can meet structural requirements without relying on cold sprayed material. Cold spray failure results in no functional impairment.
3. Non-Critical structural. Cold spray deposit carries load in this application. Failure of cold spray or cold-sprayed component does not result in functional impairment or pose a danger to personnel.
4. Semi-critical.
5. Critical.

Table A3.1. Recommended process control and acceptance criteria for Cold Spray

Lincoln Pillar	Requirement	Coating Restoration (Non-Critical)	Non-structural dim. rest. (Non-Critical)	Non-Critical structural	Semi-Critical	Critical
Stability/ Producibility	Fixed Process	Required	Required	Required	Required	Required
	Vendor Qual.	Required	Required	Required	Required	Required
Producibility/ Predictability	Procedure Qual.	Required	Required	Required	Required	Required
Predictability	Adhesion Strength	> 5 ksi	> 8 ksi	>10 ksi	Substrate UTS	Substrate UTS
	Porosity/ Oxides/ Incl.	N/A	CEO req.	CEO req.	<2%	<0.5%
	Linear Defects in deposit	N/A	200x exam < 0.050 in	200x exam < 0.030"	None @ 200X	None @ 200X
	Surface Finish	N/A	Dwg. Req.	Dwg. Req.	Dwg. Req.	Dwg. Req.
	Macro Process Check	Bend Test	Bend Test	Adhesion Test for every lot	Adhesion Test on witness coupon for each part*	Adhesion Test on witness coupon for each part*
Property Characterization	Mechanical	N/A	Required	Required	Required	Required
	Corrosion	N/A	Required	Required	Required	Required
Supportability	Service life testing	Environmental Durability	Wear resistance, Corrosion	Tensile, Fatigue, Fracture Toughness	All mech and corrosion design props. Component test	A-basis mech and corrosion design props. Component test

\* Witness coupons must be processed at the same time as the part. Witness coupons made on run off tabs are recommended.



## **APPENDIX 4**

### Guidance for Process Substitutions

## **4.0 General Considerations for Substituted Processes**

### **4.0.1. Rationale for Risk**

Process substitutions are considered point solutions, due to their dependence on the application. For example, just because Company A was able to change welding processes doesn't mean Company B can do it with low or moderate risk. Subtle changes to processes are a significant driver of Air Force mishaps.

The pace of technology development to reduce acquisition and sustainment costs as well as to comply with new environmental restrictions, laws and policies, has resulted in many process substitution alternatives that do not have accepted standards and/or USAF guidance documents for qualification. Therefore, until specific USAF guidance documents and/or USAF-accepted industry standards are produced to cover new or novel processes, USAF and industry engineers should coordinate all process substitutions with AFRL/RX [33].

## **4.1 Laser Cutting**

### **4.1.1. Rationale for Risk**

For metallic materials, ensure defects from the cutting process are mechanically removed. Defects common in laser cutting include recast layer and degraded surface integrity. Laser cutting will result in a heat affected zone and distortion and may cause material specific problems such as alpha case in titanium [34]. These issues must be accounted for through process evaluation and experimentation to understand mechanical property debits. Proper execution of these requirements for many materials is expected to show that laser cutting is not cost-competitive with traditional mechanical cutting methods. Any proposed use of laser cutting must be carefully examined.

## **4.2. Water Jet Cutting**

### **4.2.1. Rationale for Risk**

The cut edge will be cold worked and the work can be quite deep under some cutting conditions. The cold work combined with the surface condition, finish and entrapment of particles can decrease the fatigue life of the part. In some cases, the parts may be re-heat treated after water jet cutting to relieve the residual stresses at the edges. This raises additional concern for re-crystallization and grain growth during heat treat in the cold worked areas, the loss of any mechanical stress relief in the original material (e.g. - TX5X), and the opportunity to improperly heat treat. A tightly controlled process

specification and an understanding of the effect on mechanical and physical properties must be in place before water jet cutting is used on aircraft parts.

### **4.3. Paint Removal**

#### **4.3.1. Rationale for Risk**

If a mechanical process is proposed to replace a chemical process, the effect of mechanical work on the substrate materials must be characterized [35]. If a thermal process is proposed to replace a chemical process, in addition to the tests required to qualify the chemical process, tests shall be accomplished to evaluate the potential thermal effects. Multiple coating/strip cycles multiple be evaluated. Some paint removal processes, such as pulsed laser, may be both mechanical and thermal. Specifications to help guide the qualification process are shown in the reference section.

#### **4.3.2. Applications Evaluated**

Robotic continuous laser paint removal has been evaluated for use at OO-ALC. Experimental trials to determine effective paint removal processes that minimize impact to substrate materials took approximately seven years, but have resulted in a capability to depaint 7xxx, 2xxx aluminum alloys and graphite/epoxy composites with service temperatures greater than 350°F. The appropriate application of these technologies requires significant automation, process control, quality assurance and process specification development.

Robotic continuous laser depainting has been approved for use by an AWB-1015 change evaluation team.

### **4.4. Alternative Plating/Coating**

#### **4.4.1. Rationale for Risk**

For proposed replacement plating/coatings, the characteristics of the proposed plating/coating should be compared to the current plating/coating. This comparison should include, but not be limited to, hardness, thickness, post-processing requirements (densification, sealing etc.), potential introduction of new failure mechanisms on the base metal (e.g., re-embrittlement of steels, de-alloying of aluminum alloys, cold work, etc.), removal requirements, effect on NDE, introduction of hydrogen or other chemical interactions, etc.