Straightening of Investment Casting Ni-based Superalloys

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Bachelor of Science

By

Janessa Cabrera and Silvia Squillaci

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ABSTRACT

Samples belonging to four different designs of afterburner flaps, available in the as-cast, solutionized and aged conditions, underwent 4-point bend testing to fracture to investigate straightening. The average maximum load values of the second design samples in the as-cast, solutionized and aged conditions were respectively 33 kN, 29 kN and 27 kN. Regarding the fourth design samples, the average maximum load for the as-cast, solutionized and aged conditions were respectively 23 kN, 28 kN, and 25 kN. The other parameter measured during testing was the maximum extension at fracture. All as-cast samples belonging to the second design fractured at values between 5 and 7 mm, while all aged samples fractured at values between 4 and 6 mm. Independently of the design, most solutionized samples did not fracture at an extension of 9 mm or below; for such samples, 9 mm was the value used as the maximum extension. One-way ANOVA statistical analysis performed on the maximum extension data set revealed that design did not have a significant effect on maximum extension data. This analysis also revealed a significant difference between the solutionized and aged conditions among the two designs, from which it was extrapolated that it is optimal to straighten in the solutionized condition opposed to the aged. The same analysis was performed on the maximum load data set but was inconclusive due to the mean maximum load value of the as-cast condition being the highest value for Design 2 and the lowest value for Design 4. A hardness test was performed to determine the relative positioning of the maximum load data based on heat treatment condition. Due to a positive correlation between hardness and maximum load, it was expected that the ranking of the heat treatment conditions would start with aged as the highest value, then as-cast, followed by solutionized. Neither the maximum load data set for Design 2 nor 4 followed this trend; however, it was observed that while design played a significant role for the as-cast condition, it did not play a significant role for the solutionized and aged conditions. It was therefore concluded that, in general, heat treatment condition was more influential than design on both maximum load and maximum extension data sets, and more samples for testing were required for better accuracy of the results.

Key words: straightening, semi-automated press, Ni-based superalloys, Rene 41, afterburner flaps, as-cast, solutionized, aged, cracks, weld repair, fluorescent penetrant inspection, re-work cycles, investment casting, 4-point bend test, materials engineering
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1. Introduction

The aerospace industry is an ever growing market requiring greater precision production and improved quality parts. The nickel-based superalloy system has been used for applications such as engine turbine blades specifically for their high resistance to creep and corrosion at elevated temperatures. In fact, Ni-based super alloys typically make up 40-50% of the total weight of aircraft engines and are used most extensively in the combustor and turbine sections of the engine which are consistently subjected to elevated temperatures.\(^1\) Creep-resistant turbine blades and vanes make up the majority of the Ni-based superalloy components in aero engines.

The components discussed in this report are made of Rene 41 grade alloy and are fabricated by the investment casting process. This process enables the production of intricate geometries having tight tolerances and is essential for the introduction of elaborate cooling schemes that control the overall grain structures formed. In general, Ni-based superalloys are capable of being produced with equiaxed (also known as polycrystalline) grains or columnar grains, or as single crystals in which all high-angle grain boundaries would be eliminated.\(^1\) Grain boundaries act as nucleation sites for defects to accumulate, lowering the creep resistance at high temperatures. The grains of an equiaxed crystal structure are coarse compared to a columnar crystal structure indicated by the coarser surface texture (Figure 1). In application, the turbine blades nearest to the turbine engine (hottest region) would be single-crystal whereas those further from the turbine (cooler region) would likely be equiaxed.\(^2\) Another interesting application is polycrystalline turbine disks on which the blades are attached, connecting to the turbine shaft.
In the 1950s, a series of Rene and Waspaloy Ni-based superalloys were developed by General Electric and Pratt & Whitney, respectively. Rene 41 is a precipitation hardened nickel-based superalloy designed for use in highly stressed environments at elevated temperatures. These regions can reach temperatures as high as 1800°F which is 72% of the melting temperature of Rene 41. The composition of Rene 41 is represented by the ranges of elemental content (wt%) in Table I.

Table I. The Compositional Ranges of Rene 41 (wt%)
1.1 Investment Casting

Investment casting dates back 5000 years ago, when it was used by the Egyptians to produce intricate gold jewelry. Among the advantages of this process, investment casting offers high dimensional tolerances, internal and external complexity of the casting and a wide alloy selection, which includes those alloys that cannot be forged or are too difficult to machine. In this process, a wax pattern is coated with a ceramic slurry and it is then melted after the latter hardens; the resulting ceramic pattern constitutes a mold into which molten metal is poured, giving the cast part a unique shape (Figure 2).

![Figure 2. The investment casting process steps flow from left to right, top to bottom.](image)

1.2 Manufacturing and Properties of Wax Patterns

Pattern materials currently used are commonly made of wax or plastic. Waxes are generally preferred to plastics due to their low melting temperatures and low melt viscosities, which makes them suitable to be blended with other materials and melted without cracking the thin ceramic shell mold. Waxes used in investment casting usually fall into two categories: paraffin waxes and microcrystalline waxes. Given their different properties, wax patterns are usually a blend of the two in order to achieve better properties. While paraffin waxes have low cost, high lubricity and low melt viscosity their greatest drawbacks are that they are brittle and are susceptible to shrinkage. On the other hand, microcrystalline waxes can provide toughness attributed to their high plasticity. Although a blend of the two materials is beneficial to the properties of wax pattern, the latter is usually deficient in two areas:
1. Strength and rigidity, vital for thin, fragile patterns
2. Dimensional control

To improve the properties above, waxes are often blended with additives, such as plastics, resins, antioxidants, and dyes. While plastics, such as polyethylene and nylon, can improve the wax’s strength, resins and fillers can greatly reduce surface cavitation caused by solidification shrinkage. Fillers are preferred due to their higher melting points and insolubility in wax, as opposed to resins, that have a wide range of viscosities, which vary with the temperature, and softening points. Commonly used resins are coal-tar resins and those derived from trees, while commonly used fillers include spherical polystyrene and hollow carbon micro-spheres.\(^5\)

The production of wax patterns can be achieved through several techniques, depending on the amount of time a given pattern will be in use. Patterns that must be in use for longer periods of time are usually produced by injecting waxes into metal dies whose cavity is of the same shape as the cast part’s desired final shape (Figure 3a). In contrast, experimental or prototype patterns are produced with advanced techniques, such as selective laser sintering (SLS) and stereo lithography assembly (SLA). SLS and SLA are commonly referred to as “3D printing” or “additive manufacturing”, and consist of building the desired pattern through the deposition of fine layers of a given material.

The different patterns that are produced through dies are prepared for assembly according to their size. Large patterns are processed individually, while six to thirty small and medium sized patterns can be wax welded to the same runner, forming a tree or cluster (Figure 3b).\(^5\) To clarify, wax welding is the process of melting wax at the interface between two components and pressing them together until it solidifies.
1.3 Manufacturing and Properties of Ceramic Shell Molds

The process of making shell molds is carried out manually or robotically. Foundries are gradually adopting robots, which increase productivity, produce more uniform coatings and allow greater amounts of parts to be processed at the same time. Shell molds are made of several coatings, each made of a fine ceramic layer covered with coarse ceramic particles (also called stucco); the number of coatings varies depending on the desired thickness of the mold (Figure 4). Shell molds are obtained by immersing each tree assembly into a ceramic slurry; excess slurry is drained off to obtain a fine ceramic layer around the assembly. This layer, which represents the inner face of the mold, is then immediately immersed in a fluidized bed of stucco particles- or sprinkled with them from above. Stucco helps avoid further runoff of the slurry and prevents it from cracking; in addition, it increases shell thickness and provides bonding between individual ceramic layers. However, a stucco is not applied on the final coat (also called “seal coat”) to prevent loose particles from accumulating on the surface of the mold.\textsuperscript{5}

Both slurry and stucco are made of refractory materials, the most common being silica, zircon, alumina and various aluminum silicates. Silica is often used in the form of fused silica, obtained by melting of natural quartz and then solidifying it to form silica glass. For slurries, the glass is ground to form a powder, while it is crushed and screened for stucco particles. Among the advantages of fused silica are its low coefficient of thermal expansion, reducing the susceptibility
to thermal shock. Additionally, silica has a high solubility in caustic solutions which aids in removing the ceramic shell residues from the surface of castings.\(^5\) 

![Figure 4. Ceramic shell mold. The bulky structure of the mold following the buildup of several slurry-stucco layers.\(^8\)](image)

Zircon occurs naturally in sand form and it is often used in prime coats as a stucco; its properties include high refractoriness, thermal conductivity and resistance to wetting by molten metals.\(^5\) In addition, zircon is inert to chemical reactions, which minimizes metal-mold interaction during solidification. Metal-mold interactions are critical in large castings, where the solidification time is longer and allows for the mold to be in contact with the metal for longer periods of time. This interfacial reaction is the cause of defects such as dimensional inaccuracies, surface roughness, sand penetration and fused sand on steel castings.\(^9\) Zircon is also used in slurries, often with silica and aluminosilicates. The latter are composed of mullite (\(\text{Al}_2\text{O}_3\cdot2\text{SiO}_2\)); cost and refractoriness increase with increasing alumina content. Compared to aluminosilicates, alumina is more refractory and better minimizes metal-mold interactions.\(^5\)

### 1.4 Pattern Removal

After the last coat is applied, shells are left to dry for 16 to 48 hours before the wax pattern inside them is removed, in order to prepare them for the high stresses they will be subjected to during pattern removal. During this operation the mold is heated to liquify the wax, which leads to an expansion differential, since waxes have a much higher thermal expansion than that of refractories. As a result, the mold will undergo immense pressure that can crack or, in more extreme cases, destroy the mold.\(^5\) For this reason, current techniques of pattern removal aim to
melt the surface layers of the wax so that the rest of the pattern is able to expand and melt without cracking the shell. The most widely used method is autoclave dewaxing, which consists of placing molds in a jacketed vessel filled with saturated steam and equipped with a steam accumulator to ensure rapid pressurization. A pressure between 550 and 620 kPa is reached within 7 seconds, and molds are dewaxed within 15 minutes; molten wax is collected through an automatic wax drain valve to potentially be reused.

1.5 Mold Firing
Dewaxed ceramic shells are fired to burn off residual wax, to remove moisture and organic compounds in the slurry, to sinter the ceramic and preheat the mold before casting. In some cases, all of these actions are carried out by only one firing, while other times preheating is accomplished in a second firing; this occurs after the mold has cooled down and has been inspected. If cracks are found, they can be repaired with ceramic slurry.

1.6 Melting and Casting
In modern foundries, the melting of Ni-based superalloys, such as Rene 41, occurs in Coreless type Induction furnaces, which have capacities ranging from 15 to 750 lb and melting rates of about 3 lb/min. The casting process takes place in batch and semi-continuous interlock furnaces, which provide a vacuum environment for those alloys that cannot be cast in air, such as $\gamma'$-strengthened Ni-based superalloys, some cobalt alloys and refractory metals. The ability to produce intricate, thin sections in investment casting can be enhanced by processes such as vacuum-assisted casting. This process consists of placing the mold in an open chamber, that is then sealed with plate and gaskets so that only the sprue (opening of the mold) is exposed to ambient air. The molten metal is then poured, while the vacuum evacuates air through the mold, which is responsible for a pressure differential between the mold and the metal; this will help the latter to fill thin sections.

2. Post-casting Operations: Overview
Post casting operations account for about 40 to 60% of the costs related to the production of investment cast parts and consist of several operations. The order by which these steps are
performed is determined by the optimal cost-savings route, and for this reason it varies with the type of casting.  

A. **Knockout** Although the shell might spall off during cooling, most of it is still present at the end of the investment casting process, and it is usually removed with a vibrating pneumatic hammer.  

B. **Cutoff** Superalloys are cut off from the gate with abrasive wheels that operate at about 3500 rpm. In the case in which the cutting wheel cannot reach the gates, the parts are cut through torch cutting.  

C. **Straightening** Executed only when necessary, this process is performed at room temperature on parts either manually or with hydraulic presses.  

D. **Heat treatment** Depending on the application, a given part will undergo specific heat treatment steps to attain the necessary properties.  

E. **Abrasive cleaning** Steel or iron grit as well as alumina or silica sand are used in pneumatic and centrifugal blasting machines to remove scale produced during heat treatment.  

3. **Post-Casting Operations: Common Defects in Investment Casting**  

3.1 **Origin of Defects**  
A variety of defects may originate during the investment casting process. For instance, ceramic inclusions or slag may form while the hot metal is poured into the investment mold. A ceramic inclusion is a piece of the shell that has broken off while slag refers to any oxides that preexisted in the stock alloy that have ended up embedded or on the surface of the casting. If a large enough piece of the shell or wax pattern formed breaks off, the shape of the casting may be compromised. Furthermore, molten metal may flow out from crack into the other layers of the mold and solidify producing excess metal, known as metal fins, on the surface of the finished part (Figure 5). If allowable, metal fins can be removed by machining down the rough feature, however, many of the complex geometries such as ribbed sections and corners pose a challenge for the removal of this defect.
The wax mold material has a tendency to shrink during solidification which compromises the accuracy of the investment cast. In order to reduce the probability of shrinkage and cavities forming in the mold, the dimensions of the wax pattern design are enlarged.\textsuperscript{5} If these type of defects form, it is during the final stages of solidification and appear as holes and depressed regions within the finished part.\textsuperscript{9} Once the casting has been removed from the mold, it is common to find burrs (excess, positive metal) along the surfaces where two halves of a mold come together. These defects are usually completely removed along with the gating by using an abrasive tool.\textsuperscript{2} Some additives and coatings have proven to be effective in reducing the metal-mold interaction. For example, an iron oxide may be added to reduce the potential of forming metal fins on the surface of the casting.\textsuperscript{15} Adding an iron oxide, effectively softens the mold walls at elevated temperatures, increasing the mold wall flexibility and reducing metal fin formation.\textsuperscript{9}

![Surface of the Part](image)

\textbf{Figure 5.} Metal fins formed on several features of the cast part.\textsuperscript{15}

By far, the most negatively impactful defect found in a part are cracks which can propagate during post-cast processing, leading to part failure if not properly fixed. Currently, the widely used method of repairing cracks is by weld filling the defect with the same material as the casting, then machining down any build up to surface tolerances.\textsuperscript{16} A successful weld repair shows no interference with the overall strength of the casting. However, weld repairs require a certified operator and excess stock material making it a costly process. In the case of a part only being partially fixed, more defects may be introduced into the casting after the weld repair.\textsuperscript{16} These defects are usually formed or worsened during subsequent heat treatments.
3.2 Methods for Detecting Defects

Following the investment cast process most parts contain an array of defects. Many factors influence the formation of defects during investment casting so standardized inspection processes are performed to detect them. First a visual inspection checks that all features of the part, such as the surface roughness, are within dimensional tolerances. The process typically involves mounting the part in a check fixture and inspecting the features with go/no go gauges. During this inspection, the part is checked for macro-scaled deformities such as bowing or twisting and is checked for defects such as linear discontinuities, positive or negative metal, and surface pits. According to the ASTM A997, investment cast parts that meet the criteria laid out in Table II, are acceptable and will move on to further inspection. More than one acceptance level may correspond to different surfaces of the same casting. As implied, visual inspection is performed to check for cracks or flaws before or after the heat treatment process.

<table>
<thead>
<tr>
<th>Surface Feature</th>
<th>Level II</th>
<th>Level III</th>
<th>Level IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Pits</td>
<td>0.030 in. (0.76 mm) diameter by more than 1 per in.² more than 1 per in.² more than 4 per in.²</td>
<td>0.060 in. (1.52 mm) diameter by more than 1 per in.² more than 1 per in.² more than 4 per in.²</td>
<td>0.060 in. (1.52 mm) diameter by more than 1 per in.² more than 1 per in.² more than 4 per in.²</td>
</tr>
<tr>
<td></td>
<td>(645 mm²)</td>
<td>(645 mm²)</td>
<td>(645 mm²)</td>
</tr>
<tr>
<td>Positive Metal</td>
<td>0.030 in. (0.76 mm) diameter by more than 1 per in.² more than 1 per in.² more than 4 per in.²</td>
<td>0.060 in. (1.52 mm) diameter by more than 1 per in.² more than 1 per in.² more than 4 per in.²</td>
<td>0.060 in. (1.52 mm) diameter by more than 1 per in.² more than 1 per in.² more than 4 per in.²</td>
</tr>
<tr>
<td></td>
<td>(645 mm²)</td>
<td>(645 mm²)</td>
<td>(645 mm²)</td>
</tr>
<tr>
<td>Parting Line</td>
<td>0.005 in. (0.13 mm)</td>
<td>0.010 in. (0.25 mm)</td>
<td>0.020 in. (0.51 mm)</td>
</tr>
<tr>
<td>Ejector Pin Marks Height or Depth</td>
<td>0.015 in. (0.38 mm)</td>
<td>0.030 in. (0.76 mm)</td>
<td>0.045 in. (1.14 mm)</td>
</tr>
</tbody>
</table>

Abbreviation: Width

In order to check for defects that are not visually detectable, the surface of the investment cast part is inspected by Fluorescent Penetrant Inspection (FPI). This test reveals defects on, or exposed to the surface, such as positive or negative metal, porosity, ceramic inclusions, slag and cracks which may have originated during the investment casting process, gating removal, straightening process, or heat treatment cycle. FPI is a reliable, non-invasive method for
detecting surface-breaking defects and inspecting weld integrity, cold working defects and cracks.\textsuperscript{12} To clarify, the weld sites are inspected to ensure completeness of a crack repair.

During this process, the non-porous casting is dipped in a fluorescent dye which is drawn into the defects by capillary action.\textsuperscript{5} After adequate penetration time, excess penetrant is wiped away then a developer is applied in order to draw out the trapped penetrant solution. Once drawn, the volume of penetrant and developer held within a defect is displayed on the surface of the part at the location of the defect.\textsuperscript{18} Additionally, the interaction between the developer and penetrant intensify the fluorescence effect.\textsuperscript{19} After the sample has fully dried, the defective area is examined visually in an enclosed darkroom under ultraviolet radiation (also known as black lighting); the excited dye emits neon light contrast to the dark background (Figure 6).\textsuperscript{5}

![Figure 6](image)

\textbf{Figure 6.} After the penetrant fully dries, the location of a surface crack may be revealed under black lighting.\textsuperscript{19}

The third inspection technique is X-ray radiography which employs x-rays, that do not damage the part itself, producing a digital image of the internal conditions to detect any subsurface defects.\textsuperscript{17} This method is capable of detecting all the aforementioned defects that are formed closer to the core of the part.\textsuperscript{5} In general, x-ray radiography is performed only if the part does not pass the other two inspection methods. Moreover, if the part passes x-ray radiography, no further checks are required and it is passed along to further processing.
4. Post Casting Operations: Improving Straightening

4.1 Problem Statement

During inspection, ceramic inclusions, oxide particles, veining, twisting, bowing and cracks are discovered within the casting, originating from one or more steps of the investment casting process. Among these defects, it is within our scope to address PCC Structurals’ concern with cracks generated during the straightening process. Straightening is a cold working process intended to fix as-cast parts exhibiting twisting and bowing. Bowing (concave or convex bending) is a planar deformation which is simpler to correct in contrast to twisting, which is a non-planar defect. Many of the cast parts have thin sections with tight tolerances (critical as 0.06 inch), and not every defect can be visually detected. In order to meet the dimensional criteria, the part is straightened by skilled operators using hammers or an H-frame press (Figure 7). During this process, cracks are induced because the operators have little data on the limitations of a given part, leading to variation in deformation technique and different production times for each part.

Like a 3-point bend test, a given part sits on two support pins and is deformed by a loading nose above the part. The loading nose presses on a protective block which covers the non-flat protruding features (Figure 8). In this way, the load from the loading nose are evenly distributed
across the part, like a 4-point bend test. For this reason, the test specimens were 4-point bend tested in order to simulate the action of straightening with an automated press.

![Figure 8](image-url)

**Figure 8.** A loading nose pressing on the protective block which evenly distributes the load across the part.

Upon removal from the mold, a given part is straightened to its final dimensions then subjected to a series of heat treatments (solutionized and then aged). Most parts have a complex geometry containing stress concentrating features such as thin sections, sharp corners, ribbed support, holes, hollow sections, and asymmetry (Figure 9). These particular features tend to be the location of failure on most parts during the straightening process. Due to the formation of cracks following straightening, various treatments are required to repair the crack and send a given part to final heat treatment. Ideally, the part will undergo a single straightening and inspection sequence following each heat treatment, however, in the case a crack is discovered, it must be weld-repaired then solutionized before undergoing any additional cycles of straightening and inspection. The weld repair, heat treatments, and additional straightening and inspection sequence are called rework cycles which are one of the most crucial factors affecting PCC’s cost-saving goals. For reference, the average part undergoes 3-5 rework cycles; if reduced by half for all components in the flap family, alone, PCC could save close to $100,000 per year.
4.2 Project Goal

In order to meet these cost saving requirements, the end goal for PCC is to generate a repeatable, effective straightening process that takes into account the combined effects of part geometry and heat treatment condition. The scope of this project included testing four different designs, each subjected to three different heat treatment conditions (as-cast, solutionized, aged) using one strain rate - a total of 12 unique samples. Each sample underwent 4-point bend tests, which simulates straightening in a semi-automated press, in order to determine the optimal heat treatment condition to straighten in. More precisely, the intention was to prove if it is significantly different to straighten in the solutionized versus in the as-cast condition and if it is significantly different to straighten in the solutionized versus the aged condition.

5. Experimental Procedure

5.1 Samples Preparation

The molds used were rapidly produced by stereolithography assembly (SLA), as shown in Figure 10. The samples were assembled in a wax mold and then investment cast (Figure 11). A summary of the number of samples tested for each heat treatment condition and design is outlined in Table III.
Figure 10. Rapid prototype patterns of two different designs. The rectangular protrusions at the top and bottom of each sample are the gates; at this location, following investment casting, each part is cut off from the casting tree.

Figure 11. a) Fully assembled wax mold. b) Mold after the application of two coats of ceramic slurry.

Table III. Number of Samples Tested in Each Heat Treatment Condition and Design

<table>
<thead>
<tr>
<th>Design</th>
<th>As-cast</th>
<th>Solutionized</th>
<th>Solutionized and Aged</th>
<th>Total Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
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</tr>
<tr>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

Following the investment casting process some of the samples required weld repairs. These weld repaired areas were mapped out on the general schematic of each sample which will later be compared to the location of crack propagation.
Each of the samples was given a one-digit or two-digit sample number having no correlation to its given heat treatment condition or design. This sample number was used to identify each unique sample. It was pertinent to the project to analyze groups of samples in terms of design and heat treatment condition. But individual samples within these groups were analyzed for explanation of outliers and anomalies discovered in the data.

5.2 Sample Geometry
When designing a test specimen, common features seen in the different flap family members were considered in order to best simulate the geometry of common parts. Design 1 was the simplest, with the intention of producing a geometry whose behavior was predictable. For this reason, the first design was an I-beam on top of the base frame which still captured the thin-walled feature seen among all the flap family component (Figure 12). The flap components within the scope of our study had a symmetrical slanted surface; this feature was captured in Design 2 (Figure 13). A final observation made was that most parts had stress concentrating features; a common feature being a pair of thin-walled support ribs which was included in Design 3 (Figure 14). Design 4 captured both the slanted surface and support rib features as well as other features, like asymmetry and a slotted hole above one of the pair of ribs, to better approximate the complete geometry of a common flap family member (Figure 15).
Figure 12. Design 1: I-beam on top of the base frame.

Figure 13. Design 2: Trapezoidal I-beam on top of the base frame.
Figure 14. Design 3: Trapezoidal I-beam on top of the base frame including a pair of support ribs.

Figure 15. Design 4: Asymmetric trapezoidal I-Beam with slotted hole centered above right pair of support ribs.
Even though Design 1 contains thin sections, overall its geometry is far from approximating that of a flap component. This design was produced to address the concern of 4-point bending a slanted surface. It was in our interest to see how the test would initially run given the loading pins would be contacting a flat surface like most standardized 4-point bend tests. Within the same round of testing, a sample of Design 2 and 3 were tested successfully, proving that it was possible to test on a slanted surface. For this reason, we went forward with testing the remaining Design 2, 3, and 4 samples only and did not include any of the Design 1 samples in further testing or analysis. It should be noted that besides having common geometric features, such as thin sections, all designs had the same length, width, and wall thickness (0.06 inches).

5.3 4-Point Bend Fixture Setup
A cross-head displacement rate of 5 mm/min was used for testing all samples. The standardized 4-point bend test fixture was used on an Instron mechanical testing system having a maximum load capacity of 50 kN (Figure 16). For Design 2 and 3 the loading span was set at a length of 38 mm and the support span was set at a length of 76 mm. This setup worked for both these designs but not the fourth design, due to the asymmetric protruding feature.

To address the asymmetric protruding feature of Design 4, the support span was initially set at 10% the length of the part overhanging the left support pin (Figure 16). Given the protruding feature was located on the left-hand side, the right support pin was fixed at an arbitrary span similar to that of the other designs, relative to the left support pin. Furthermore, the loading span was set to an arbitrary value similar the setup for Designs 2 and 3, but centered about the protruding feature rather than symmetric about the center of the part. The loading nose was then hovered just millimeters above the part and each loading pin’s individual position was fine-tuned so that each pin was touching the part at the same height. For each sample, the loading span had to be repositioned which was measured as a function of the amount of overhang over the left support pin varying from 15 to 20 mm.
Each 4-point bend test generated a load-extension curve from which maximum load ($P_{\text{max}}$) and maximum extension ($\delta_{\text{max}}$) values were recorded. Each test was executed until a given sample failed. For clarity, failure of the part for the as-cast and aged samples was described as the $P_{\text{max}}$ and $\delta_{\text{max}}$ values at which a crack had propagated to, effectively stopping the testing software. The definition of failure for the solutionized samples was the $P_{\text{max}}$ at which the $\delta_{\text{max}}$ was close to or at 9mm. The $\delta_{\text{max}}$ values were obtained from the load-extension curves. These measurements were all adjusted to account for the amount of extension (flat line section) before the test had started.

5.4 Measurement of Springback

Following 4-point bend testing, springback (SB) values were collected for Designs 2 and 3. Springback represents the elastic recovery of a given sample after it has been plastically deformed. This value was described as the final height of the sample following testing ($H_f$) minus the initial height ($H_i$). For clarity, $H_i$ is the height of the sample before the loading nose was released, while $H_f$ was measured after being removed from the Instron (Figure 17). The measurement of $H_f$ was taken with dial calipers at roughly the center of each sample between the top (slant) and bottom (base frame) wall thicknesses (Equation 1). The initial height was measured as the difference between the height of the sample prior to testing (accounting for the top and bottom wall thicknesses) minus $\delta_{\text{max}}$ (Equation 2). The height of the sample prior to
testing had a constant value of 0.75 mm for Design 2 and 3 while the the $\delta_{\text{max}}$ was measured by the software.

![Figure 17. Schematic of how springback was measured for Design 3.](image)

\[
\text{Spring Back} = H_f - H_i \quad \text{(Equation 1)}
\]
\[
H_i = 0.75 \text{ mm} - \delta_{\text{max}} \quad \text{(Equation 2)}
\]

The difficulty about collecting these measurements was that the dial calipers used were too large to fit between the top of the base frame and the underside of the top surface of a given part. This disabled the two teeth from lying flush with the inner surfaces, rather, they touched the part at an angle adding some error to the data. For Design 3, this measurement was taken on the left side of the support rib. For consistency, the point of measurement of each sample was taken from the front at roughly the center. The measurement was taken from the front also because this side of most samples warped downward while the back end was warped upward.

For Design 4, the springback was to be measured to the left of the support rib, close to the center of the part, like the method used for Design 3. However, there was a second pair of support ribs and the protruding feature was not centered about the part. At first it seemed most logical to measure the springback at the protruding feature, however, for the case of all Design 4 samples, this feature displayed little deformation. It was decided that such a small deflection was not representative of the real springback data for Design 4 and was thus not recorded or used in the analysis.
5.5 Statistical Analysis
One-way ANOVA statistical analysis was performed for the properties $P_{\text{max}}$ and $\delta_{\text{max}}$. The analysis was performed using a p-value of 0.05 and with two main effects: heat treatment condition and design. A Tukey’s analysis was performed to determine if there was a significant difference between the combined effect of these main effects on both $P_{\text{max}}$ and $\delta_{\text{max}}$. If there was no significant difference in the interaction of the main effects, further investigation was performed comparing either of the main effects to the both $P_{\text{max}}$ and $\delta_{\text{max}}$ data sets.

5.6 Hardness Measurements
Given that $P_{\text{max}}$ is a function of hardness and design, hardness measurements were taken for confirmation of the trend seen in the $P_{\text{max}}$ statistical analysis data. Hardness is affected by heat treatment condition but is independent of design. Hardness measurements were taken for a Design 1 sample of each condition using a Rockwell Hardness Tester on the HRC scale; five hardness readings were taken for each sample.

6. Results

6.1 Observations from Load-Displacement Curves
From the 4-point bend test, load-displacement curves were generated (Figure 18). Across the three heat treatment conditions, most solutionized samples had $\delta_{\text{max}}$ values close to 9 mm; testing was stopped close to this point because the software was incapable of registering extensions beyond 9 mm (Figure 18b). The as-cast samples failed within a range of 4-7 mm (Figure 18a), similarly to the aged samples (Figure 18c). After testing the Design 3 as-cast samples, it was discovered that the span was not properly set, invalidating the results of these tests. For this reason, the Design 3 as-cast data was not reported.
While testing, an audible “ping” noise was heard corresponding to the initial formation of a crack in a given part. It was observed that this noise was also associated with a small dip on the load-displacement curves. For most solutionized samples across all designs, this was the only
indicator of crack formation since many did not fracture. On the other hand, for most as-cast and aged samples, the crack continued to propagate until a loud “bang” noise was heard, followed by the automatic termination of the test. This noise was associated with the point at which the part fractured.

Unlike the other load-displacement curves, after displaying the initial drop, the graphs for Design 4 wavered until the end of testing (Figure 19). All other designs displayed smooth curves until final fracture or until an extension of 9 mm was reached.

**Figure 19.** Load displacement curve of the solutionized Design 4 samples.

### 6.2 Observations from the Inspection of Fractured Samples

It was found that, due to their similar geometry, Design 2 and Design 3 displayed the same crack locations depending on the heat treatment condition. In fact, all solutionized samples cracked approximately at ½ of the half-length of base frame of the part with respect to the center (above the support pins), either on one side or both sides (Figure 20a). Regarding the aged samples, besides cracking at the same location of the solutionized samples, they fractured along their body, below either the left or the right loading pin (Figure 20b). In this case, the crack nucleated from the base frame at a location below a loading pin and propagated towards the slanted top surface. The as-cast samples of Design 2 displayed the same cracking behavior as the aged samples.

In Design 4, as-cast and solutionized samples showed cracks across the slot as well as on the
right of the right support rib, on the base frame (Figure 21). It should be noted that in this case, the crack was not situated above the support pin as in the case of Design 2 and Design 3. The aged samples, besides showing the same crack sites as the as-cast and solutionized samples, fractured on the left of the right support rib and cracked above the left support pin (Figure 22).

![Figure 20](image1.png)

**Figure 20.** a) Crack sites for the solutionized condition of Design 2 and Design 3. b) Crack sites for the as-cast and aged condition of Designs 2 and 3.

![Figure 21](image2.png)

**Figure 21.** Crack sites for as-cast and solutionized Design 4. a) Crack across the slot. b) Crack to the right of the right support rib.

![Figure 22](image3.png)

**Figure 22.** Crack sites for aged Design 4. The red “X” indicates that the samples also cracked to the left of the right support rib, while the orange “O” indicates that cracks were found below the left support pin, as found through FPI.
Finally, the all samples were inspected to investigate if there was a correlation between crack sites and weld sites. None of the samples belonging to Design 2 cracked at the welds, whereas Sample No. 11 (Design 3) cracked at one weld. Regarding Design 4 samples, Sample No. 18 cracked at two welds and Sample No. 32 cracked at the weld right next to the slot. Based on this observations, the more complex the design, the more samples cracked for a specific design. In addition, two of the three samples that cracked at the welds (Samples No. 11 and 32) were in the aged condition.

6.3 $P_{\text{max}}$ and $\delta_{\text{max}}$ Trends Based on Design and Heat Treatment Condition

The $P_{\text{max}}$ and $\delta_{\text{max}}$ values, as well as the springback measurements, were collected for each heat treatment condition of Design 2, 3 and 4 (Table IV, V, VI). For Design 2, the as-cast samples withstood the highest $P_{\text{max}}$, followed by the solutionized and the aged samples, while the solutionized samples displayed the highest $\delta_{\text{max}}$, followed by the as-cast and aged samples. Regarding Design 4, the solutionized samples withstood the highest $P_{\text{max}}$, followed by the aged and the as-cast samples, while the $\delta_{\text{max}}$ trend for these samples was similar to that obtained for Design 2 samples.

It should be noted that, for the solutionized samples for both designs, the average $\delta_{\text{max}}$ was below 9 mm because samples No. 5 (Design 2), 16, 17 and 34 (Design 4) displayed an abnormally low $\delta_{\text{max}}$ values. Regarding the rest of the solutionized samples, they displayed a $\delta_{\text{max}}$ below 9 mm because the test was manually stopped when $\delta_{\text{max}}$ approached this value. After comparing average springback values to average $\delta_{\text{max}}$ values, a positive correlation between the two was observed in both Designs 2 and 3 samples.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Condition</th>
<th>$P_{\text{max}}$ (kN)</th>
<th>Average $P_{\text{max}}$ (kN)</th>
<th>$\delta_{\text{max}}$ (mm)</th>
<th>Average $\delta_{\text{max}}$ (mm)</th>
<th>Springback (mm)</th>
<th>Average Springback (mm)</th>
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<td></td>
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Table V. 4-Point Bend Test Data for Design 3

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<th>$\delta_{\text{max}}$ (mm)</th>
<th>Average $\delta_{\text{max}}$ (mm)</th>
<th>Springback (mm)</th>
<th>Average Springback (mm)</th>
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Table VI. 4-Point Bend Test Data for Design 4

<table>
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<th>Sample No</th>
<th>Condition</th>
<th>$P_{\text{max}}$ (kN)</th>
<th>Average $P_{\text{max}}$ (kN)</th>
<th>$\delta_{\text{max}}$ (mm)</th>
<th>Average $\delta_{\text{max}}$ (mm)</th>
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<td></td>
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<td>7.3</td>
</tr>
<tr>
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<td>3.9</td>
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<td>Aged</td>
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<td>23.6</td>
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<td>3.1</td>
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</table>

Tukey’s analysis revealed the specific combinations of heat treatment condition and design parameters that resulted in significantly different mean $P_{\text{max}}$ values (Figure 23). Because the data set for all three conditions was required for performing a one-way ANOVA comparison, the Design 3 data was also excluded from statistical analysis. Only the pairs having the same design were analyzed. Regarding Design 2, there was not a significant difference between the mean $P_{\text{max}}$ values of the as-cast solutionized samples. On the other hand, the mean $P_{\text{max}}$ values of Design 4 solutionized and as-cast samples displayed a significant difference. In addition, there was not a significant difference between the $P_{\text{max}}$ withstood by the solutionized and aged samples for Design 2 and Design 4 (Figure 23).

The results obtained from the one-way ANOVA on the $\delta_{\text{max}}$ data set revealed that design did not have a significant effect on $\delta_{\text{max}}$, however, they revealed a significant difference between the mean $\delta_{\text{max}}$ values based on heat treatment condition. A Tukey’s comparison confirmed that for both designs, the solutionized and aged condition pair displayed a significant difference (Figure 24).
Line plots of the mean $P_{\text{max}}$ and $\delta_{\text{max}}$ data were generated to analyze the trends on the basis of design and condition. For the $P_{\text{max}}$ data set, the mean values of the solutionized samples were consistently higher than the aged samples for both designs. The $P_{\text{max}}$ line plot also shows that the lines for the solutionized (green) and aged conditions (aged) were somewhat parallel to one another (Figure 25a). However, for Design 2 the mean value of the as-cast samples is the highest.
for Design 2 and the lowest for Design 4. For the $\delta_{\text{max}}$ data set, the mean values for both designs decreased in order of solutionized, as-cast, then aged. For both the solutionized and aged conditions, the mean values of the Design 2 were consistently higher than the Design 4 samples. However, for the aged condition the mean value of Design 4 was higher than that of Design 2 (Figure 25b).

![Line Plot of Mean( Max Load (kN) )](image1)

![Line Plot of Mean( Max Extension (mm) )](image2)

**Figure 25.** a) Plot of the mean values of maximum load as a function of condition and design. b) Plot of the mean values of maximum extension as a function of condition and design.

Hardness values were taken for validation of the trend in the mean $P_{\text{max}}$ values. The solutionized condition had the lowest value, while the as-cast and aged conditions had rather similar results, all of which are summarized in Table VII. Although the hardness of the as-cast and aged conditions were similar, from this data it was extrapolated that the $P_{\text{max}}$ values should follow the this trend across the heat treatment conditions starting with aged as the highest, then as-cast, followed by solutionized.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Average (HRC)</th>
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<tr>
<td>As-Cast</td>
<td>32.1</td>
</tr>
<tr>
<td>Solutionized</td>
<td>25.1</td>
</tr>
<tr>
<td>Aged</td>
<td>32.4</td>
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**Table VII.** Mean Hardness Values for Each Heat Treatment Conditions

Like hardness readings were measured to determine the trend in $P_{\text{max}}$, the springback was measured to determine the trend in $\delta_{\text{max}}$ data. Although these values were not measurable for the fourth design, both the second and third design displayed the same trend starting with solutionized, then as-cast, followed by the aged condition. Across the heat treatment conditions,
the $\delta_{\text{max}}$ values for both Design 2 and 3 followed this trend, denoting a positive correlation between $\delta_{\text{max}}$ and springback.

7. Discussion

The one-way ANOVA test (Figure 23) shows that on average, within Design 4, as-cast samples were able to withstand a significantly lower $P_{\text{max}}$ than the solutionized samples, which supports the argument that PCC should straighten their afterburners flap parts in the solutionized condition. However, the team questioned the validity of the conclusions drawn from the one-way ANOVA test due to the significant difference between the mean $P_{\text{max}}$ taken by the as-cast samples in Design 2 and 4; while the former withstood on average the highest $P_{\text{max}}$, the latter withstood on average the lowest $P_{\text{max}}$ (Figure 25a). Since $P_{\text{max}}$ is dependent on both hardness and design, inconsistency between the two $P_{\text{max}}$ trends was caused by the significant difference between the $P_{\text{max}}$ mean values of both designs in the as-cast condition, suggesting that geometry was influential only for this given condition. In fact, there was no significant difference found in the $P_{\text{max}}$ withstood by both designs in either the solutionized or the aged condition (Figure 23). However, the hardness values were used for better insight on the relative position of $P_{\text{max}}$ values for each condition (Table VII). Due to the positive correlation between hardness and $P_{\text{max}}$, the aged samples were expected to withstand the highest $P_{\text{max}}$, closely followed by the as-cast and then the solutionized samples.

However, neither of the $P_{\text{max}}$ trends for each design was consistent with the trend correlated to hardness values nor were the $P_{\text{max}}$ trends consistent with one another (Figure 25a). The inconsistency of the results was attributed to the fact that the team wasn’t provided enough samples for each condition, nor was provided the same amount of samples for each design. This could have been the cause of the large scatter in the $P_{\text{max}}$ values in as-cast data set and the position of the line plots for each condition relative to one another.

Although the one-way ANOVA did not validate that there was a significant difference in the $\delta_{\text{max}}$ between the as-cast and solutionized samples, it showed that there was a significant difference in the $\delta_{\text{max}}$ between the solutionized and aged samples. It should also be noted that while the
Tukey’s comparison for the solutionized and aged pair showed a significant difference in the \( \delta_{\text{max}} \), the Tukey’s comparison for the as-cast and solutionized had a p-value near the threshold value indicating a significant difference (Figure 24). As in the case of \( P_{\text{max}} \) analysis, a greater amount of samples available for testing could have shrunk the scatter in the \( \delta_{\text{max}} \) data; in this way, a data range within the boundaries of the area that represents significant difference may be produced.

Except in the case of \( P_{\text{max}} \) values obtained for the as-cast condition, the \( P_{\text{max}} \) and the \( \delta_{\text{max}} \) data sets showed that design did not have a significant effect on either \( P_{\text{max}} \) or \( \delta_{\text{max}} \). This was somewhat confirmed by the fact that Design 2 and 3 displayed cracks at the same sites depending on heat treatment condition. Regarding Design 4, the as-cast and solutionized samples showed cracks at the same sites while the aged samples cracked at the same locations but displayed additional cracks. In light of this, it can be said that heat treatment condition was a determinant factor for all designs; however, while in Design 2 and Design 3 the cracks occurred in the close proximity to the support pins, in Design 4 the samples cracked mainly near stress concentration features, such as the slot and the right support rib. This indicates that, due to the greater complexity of Design 4 with respect to Design 2 and Design 3, geometry could have played a greater role in the former, as indicated by the abnormally low \( P_{\text{max}} \) of the as-cast samples belonging to Design 4.

**8. Conclusions**

1. It is unclear whether it is optimal to straighten in the solutionized or the as-cast condition.
2. When considering straightening in the solutionized condition versus the aged, based on maximum extension analysis, there was sufficient evidence supporting solutionized as the optimal condition.
3. Geometry had a significant effect only on the maximum load taken by the as-cast samples of Design 2 and 4.
References


