Low-Cost Materials for Thermoplastic Composite Tooling

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Tooling is often a substantial start up investment for new manufacturing lines, making up anywhere between 6% to 30% of total manufacturing costs. Tools like molds, dies, and fixtures represent a large amount of capital embedded into the manufacturing process. For composite heavy industries like aerospace, with low overall production volumes, this is even more true. Molds designed for the manufacture of thermoplastic composite components often employ high performance materials like the super alloy Invar and tools steels like P20. These materials are common selections thanks to their low coefficient of thermal expansion (CTE) and high hardness. However, these characteristics present challenges to some manufacturers: these high-performance characteristics lead to a much higher cost and are more difficult to machine and work. In this research, more common materials such as cast iron, 4140 alloy steel, and 6061 aluminum are proposed as possible alternatives for use in composite tooling. By characterizing the mechanical and thermal properties of these more common materials, and comparing them to these high-performance materials, this paper provides a cost-benefit analysis of the use of these common materials for composite manufacturing. This paper also analyzes the performance of composite tooling made from common materials by examining the consolidation of thermoset carbon fiber reinforced composite (CFRP) C-channel structures manufactured with tooling made with cast iron, 4140 alloy steel, and 6061 aluminum through a microscopy study. Through this research, the advantages in selecting lower cost, more easily machinable materials for composite tooling: lower initial start-up investments, quality of final composite components, and weight reduction, are evaluated and traded with respect to tooling wear and accompanying reduction in tool life.

I. Nomenclature

CFRP = Carbon Fiber Reinforced Composite
CTE = Coefficient of Thermal Expansion
AISI = American Iron and Steel Institute
IML = Inner Mold Line
OML = Outer Mold Line
HDR = High Dynamic Range

II. Introduction

As the demand for composite components continues to grow in industries like aerospace, more effort needs to be spent exploring options to increase the viability of these material systems from a manufacturing standpoint. One method to increase this viability is to reduce costs, both initial and occurring. By using common materials for use in composite tooling, manufacturing costs for composite material systems will decrease, leading to reduced component costs and a lower barrier of entry for composite research. The materials selected for analysis are widely produced and have common uses in industry. This results in low cost and high availability. 4140 alloy steel is an alloy of iron, carbon, chromium, molybdenum, and manganese. It has a high abrasion resistance and fatigue strength, making 4140

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a good potential tooling candidate [1]. 6061 aluminum is the most common grade of aluminum. While weaker than the other materials being analyzed, its common use in the automotive industry and as a structural material makes 6061 the cheapest material and easy to acquire [2]. Grey ductile cast iron is the most common form of cast iron. It exhibits a high compression strength and is commonly used in structures for machine tools [3]. Its ability to be cast could additionally lower costs as cast tools would require less machine time to manufacture. The following materials are either currently found in use in composite tooling or in a similar role in adjacent industries; invar 36 is a high nickel superalloy that is very thermally stable with a low CTE. This low CTE is why it is currently used in the aerospace industry as a composite tooling material [4]. P20 tool steel is commonly used for plastic injection molds where it is subject to high temperatures of melted thermoplastic and abrasive additives like glass and carbon fibers [5]. To compare the effectiveness of each material as a composite tool, the material properties needed will be analyzed against the materials previously mentioned. Additionally, a microscopy study of components manufactured using the alternative common materials (4140, 6061, and cast iron) will be conducted to assess the quality of representative components.

III. Analysis of Potential Tooling Materials

To begin analyzing these materials as possible candidates for composite tooling, relevant properties regarding the tool’s performance must be determined. The following properties are selected for analysis: cost per volume, CTE, hardness, and machinability. These properties play an important role in the performance of a composite tool. Tooling cost is a major component of initial investment for new production lines and can stifle new research if too large. CTE is the rate of strain a material experiences per change in temperature. CFRP materials have an extremely low CTE. Ideally the tooling material should match the composite’s CTE, therefore lower CTE materials are preferable to prevent defects in the final component. Hardness is a material’s ability to resist plastic deformation and correlates to the longevity of composite tooling. CFRPs are abrasive in nature, and materials with a higher hardness can better resist scratching, and defects caused by the CFRP. Machinability is a normalized value set by the AISI that compares the tool life, surface finish, and federate of a material to B1112 steel [6]. Lower machinability correlates to an increased difficulty in cutting the material. Materials with low machinability can accrue higher operating costs as tooling made with these materials require longer machine times, reduce cutting tool life, and can require specialty cutting tools for efficient machining. Material properties were recorded and scored against each other to analyze individual performance compared to the group.

Data	**4140 Alloy Steel**	**Grey Ductile Cast Iron**	**6061 Al**	**Invar 36**	**P20 Tool Steel**
Cost ($/in^3)	2.54	2.14	1.49	33.06	4.56
CTE (10^-6 1/°C)	12.2	11.25	23.2	1.5	12.8
Hardness (Rockwell B)	91	97	47	90	102
Machinability (%)	61	93.4	270	37.5	39

Fig. 1 Tooling materials and their respective properties.

Scores	**4140 Alloy Steel**	**Grey Ductile Cast Iron**	**6061 Aluminum**	**Invar 36**	**P20 Tool Steel**
Cost	3	4	5	1	2
CTE	3	4	1	5	2
Hardness	3	4	1	2	5
Machinability	3	4	5	1	2
Total	**12**	**16**	**12**	**9**	**11**

Fig. 2 Same materials scored against each other.

A. Cost Estimate

For this analysis, cost is attributed on a per volume basis according to McMaster Carr, a prominent material supplier. These costs were based on similar diameter rods at the shortest length available: 1 inch diameter at 6 inches in length for 4140 alloy steel, 1.25 inch diameter at 12 inches in length for grey ductile cast iron, 1 inch diameter at 6 inches in length for 6061 aluminum, 1 inch diameter at 6 inches in length for invar 36, and 1 inch diameter at 6 inches in length for P20 tool steel. While costs can fluctuate between vendors, the relative difference between material pricing is consistent.

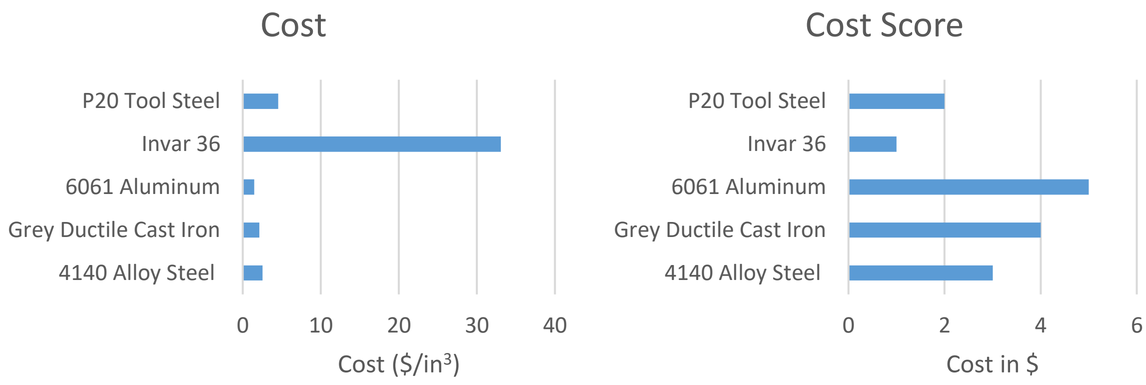


Fig. 3 Volumetric cost of each material.

Invar 36 has the largest volumetric cost of $33.06 per cubic inch, over eight times the cost of the other materials. Aluminum's cost was the lowest at $1.49 per cubic inch. Cast iron and 4140 had comparable costs at $2.14 per cubic inch and $2.54 per cubic inch respectively, with P20 twice as high at $4.56 per cubic inch.

B. Coefficient of Thermal Expansion

The CTEs of each material were compared in a similar manner, with the raw value and comparative score both considered.

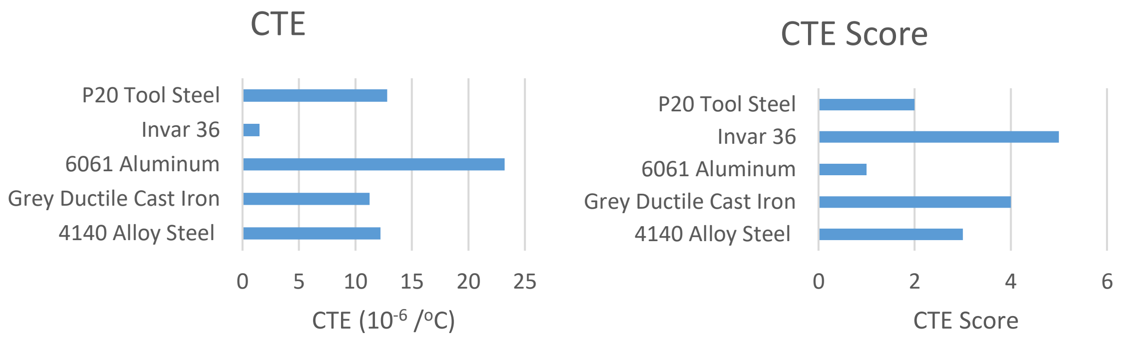


Fig. 4 CTE and calculated performance score for each material.

Invar has the lowest CTE at $1.5*10^{-6}$/ºC, demonstrating why one of its primary uses is in composite tooling. At $23.2*10^{-6}$/ºC, aluminum has the worst CTE of the set. The iron-based selections exhibit similar CTEs around $12*10^{6}$/ºC.

C. Hardness

The hardnesses of the 4140 alloy steel, grey ductile cast iron, and P20 tool steel are presented on the Rockwell C scale. The 6061 aluminum and invar 36 are presented on the Brinell and Rockwell B scales respectively. All hardnesses were converted to Rockwell B for the sake of comparison.

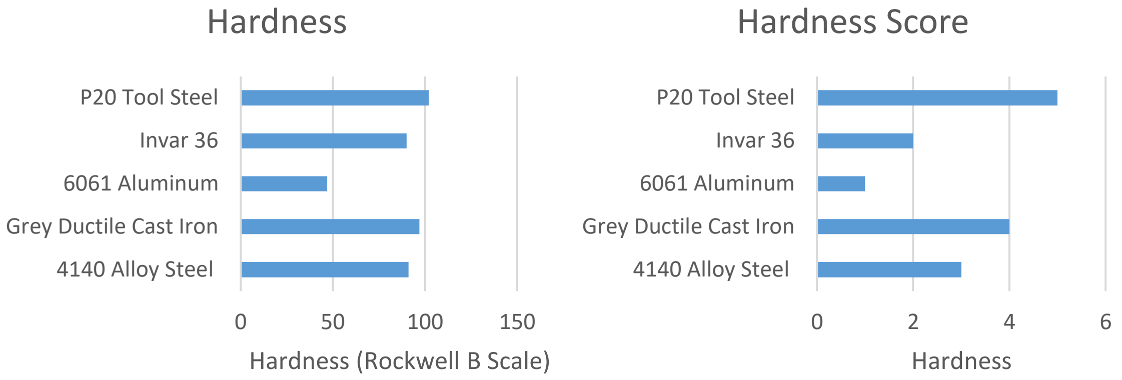


Fig. 5 Rockwell hardnesses and calculated performance score for each material.

The P20, invar, 4041, and cast iron all share very similar hardnesses, around 95 Rockwell B. P20 tool is slightly harder at 102 Rockwell B. The 6061 aluminum is much softer than the other materials at 47 Rockwell B.

D. Machinability

The rankings for machinability echo that of the volumetric cost of each material, with aluminum being the most machinable at 270% and invar being the least at 37.5%.

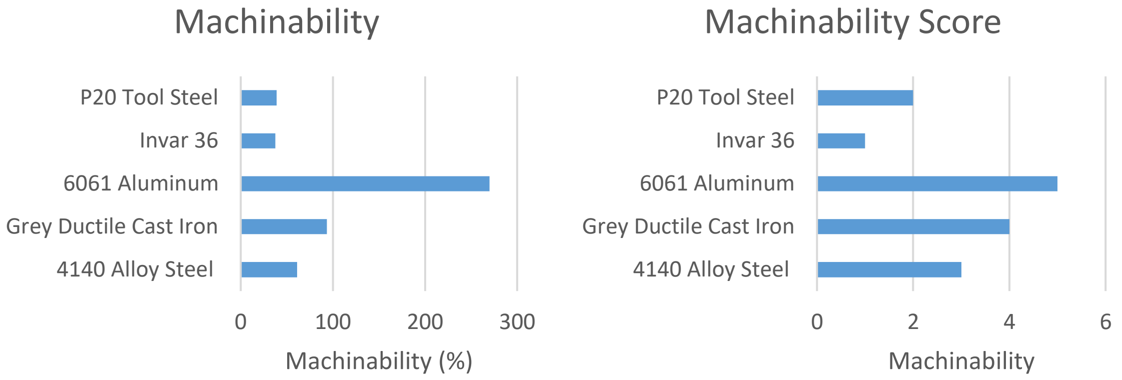


Fig. 6 Machinability and calculated performance score of each material.

P20 is slightly more machinable than invar at 39%. 4140 is harder to machine than cast iron with machineabilities of 61% and 93.4% respectively.

IV. Component Manufacturing

To test the viability of common materials for use in composite tooling, CFRP C-channel components are manufactured using molds made from 6061 aluminum, 4140 alloy steel, and grey ductile cast iron. The C-channel molds are cured via hot press which exerts both pressure and heat onto the molds. Components are then trimmed and sampled for analysis with microscopy.

E. Tooling

For this project, examples of relevant structural geometry are desired to better reflect the real-world application of the findings. The C-channel cross section is selected for its individual use as a structural geometry as well as its use as a subcomponent for geometry like I beams and squares, and its similarities to geometry like L and T stiffeners. The geometry of a C-channel cross section also provides different consolidation scenarios throughout the same component; seeing greater pressure along the web as compared to the flange, and a sharp change in fiber orientation along the corners of the component. The 6061 aluminum and 4140 alloy steel tools have an overall length of 6 inches, and the grey ductile cast iron tool has an overall length of 24 inches. All tools share the same cross section with a web of 1.6

inches, flanges of 1.25 inches, and corner radii of .125 inches. All tools are OML controlled and employ a 1 degree draft angle to aid in the recovery of components. To prepare the tools for curing, the OML and IML of each tool was coated with Loctite Frekote 710-ns to act as a mold release, preventing the material from bonding to the molds while curing.

a b c

Fig. 7 Example C-channel tooling a) 4140 alloy steel b) grey ductile cast iron c) 6061 aluminum.

F. Material and Preform

Toray 3900 T830H-6K prepreg (0/90) weave is selected for the components. While not thermoplastic, the thermoset material is still useful in comparing the performance of the three tools. A stacking sequence of $(0/90)_8$ is selected to mimic the 12 ply consolidated thickness of Toray TC 1225, for which the tools were designed for. The 0/90 ply orientation is selected to ensure that fibers are either normal or parallel to the plane undergoing microscopy. This better highlight any damage or inconsistencies in the cured component when observed under the microscope.

G. Consolidation

To cure the components, a Wabash Genesis 0.9 kN (100,000 lbf) hot press is used to apply both heat and pressure to the molds. The process recipe for the hot press cure was adapted from the autoclave recipe for 3900 T830H-6K provided by Toray. The recipe calls for a platen temperature of 350 degrees Fahrenheit at a cylinder pressure of 50 tons. These conditions are held for an hour while the composite cures.

Fig. 8 Wabash hot press being set up to run the aluminum tool.

a b c

Fig. 9 Cured components ready for trimming a) alloy steel b) cast iron c) aluminum.

H. Processing

After the components cure, excess material is trimmed away to the final C-channel geometry. This is accomplished using a Kobalt diamond bladed wet saw. Once trimmed roughly half inch samples are taken along the length using the same method mentioned before.

V. Sample Preparation

In readiness for the high-resolution microscopy analysis, the process begins with precise machining to expose the cured material and ensure uniformity in the CFRP C-channel structure samples. This is followed by a comprehensive grinding process, refining the surface texture of the samples through a progressive sequence of abrasive grits. Leading to the final stage of polishing.

A. Casting

To prepare the samples for microscopy, the samples are cast inside molds using high viscosity resin. Dye is added to the resin to increase the contrast between the samples and the resin. This casting ensures that the samples can more easily be viewed under the microscope.

B. Machining

The examination of thermoplastic carbon fiber reinforced composite (CFRP) C-channel structures began with the machining process, where a 5-flute carbide cutter on a Bridgeport knee mill was utilized. This machining operation was crucial in exposing the cured composite material and ensuring that the opposite faces of the samples were flat and parallel for subsequent grinding and polishing stages.

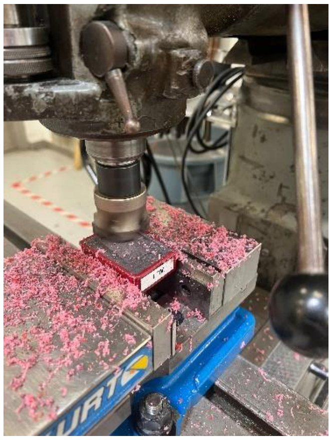


Fig. 10 Cast samples being faced on Bridgeport knee mill.

C. Grinding, Sanding, and Polishing

Following machining, the samples underwent a comprehensive grinding process to refine their surface texture in preparation for microscopy analysis. The grinding procedure entailed sequential sanding with abrasive grits, beginning at 80 and progressing through increasing levels of abrasiveness: 120, 180, 240, 800, and finally 1200, utilizing a nano-2000S machine operating at 1000 rpm. Each side of the samples were meticulously sanded, totaling six sides, 2 sides per sample, with approximately one hour dedicated to each level of grit. Subsequently, alumina abrasive powder was used to polish each side, further enhancing surface finish.


a b c

Fig. 11 Polished samples ready for microscopy a) alloy steel b) cast iron c) aluminum.

VI. Microscopy

After the meticulous preparation process, the samples were subjected to microscopy analysis using a Keyence VHX 5000 digital microscope. Digital photos of each side of every sample were captured to facilitate detailed examination and analysis. Microscopy examination was conducted at magnifications of 100x and 200x to provide insights into different aspects of the samples. At 100x Magnification, Images were captured to examine the uniformity of stitches along the length of each sample. This magnification setting allowed for the assessment of the overall quality and consistency of the stitches, providing valuable information regarding the manufacturing process and material consolidation. At 200x Magnification, Specific areas of interest, such as corners and regions displaying abnormalities within the stitches (e.g., tears, rips, gaps), were examined at higher magnification. This detailed scrutiny enabled the identification and characterization of any structural irregularities or defects present within the samples.

To enhance image quality and minimize glare, the microscope settings were optimized, including the use of HDR at a brightness of 16. These adjustments were implemented to ensure the acquisition of high-quality images that accurately captured the intricate details of the samples under examination.

VII. Results

Performance predicted by the material analysis of the 4041 alloy steel, 6061 aluminum, and grey ductile cast iron are confirmed by observing the quality of the cured C-channel samples. While some materials excelled in singular areas, their mediocracy regarding the other properties limited their effectiveness as a tooling material. Despite the low cost of the 6061 aluminum, its performance observed under magnification was poor, with large voids, areas of low fiber volume, and resin overflow. These defects could greatly compromise the structural integrity of components made using aluminum tooling, reducing the potential of aluminum as a composite tooling material. Both the 4140 alloy steel and the grey ductile cast iron exhibit well rounded material properties for use in composite tooling, and performed well during the manufacturing of the sample C-channels.

A. Material Analysis

When considering cost, CTE, hardness, and machinability as the relevant material properties needed for an effective composite tool, grey ductile cast iron had the highest combined score at 16, being the second most effective material for each category. 4140 alloy steel and 6061 aluminum scored the second highest at 12. 4140 is more well-rounded, scoring third best in each category, while aluminum has the lowest cost but below average performance in the other categories. P20 tool steel scored fourth best, having the highest hardness but scoring poorly in other categories. Invar 36 scored last due to its high cost, low machinability, and low hardness. However, it should be noted that invar performed the best in CTE by an order of magnitude. CTE is a driving factor in tooling material, and this scoring method does not account for the degree in difference between metrics.

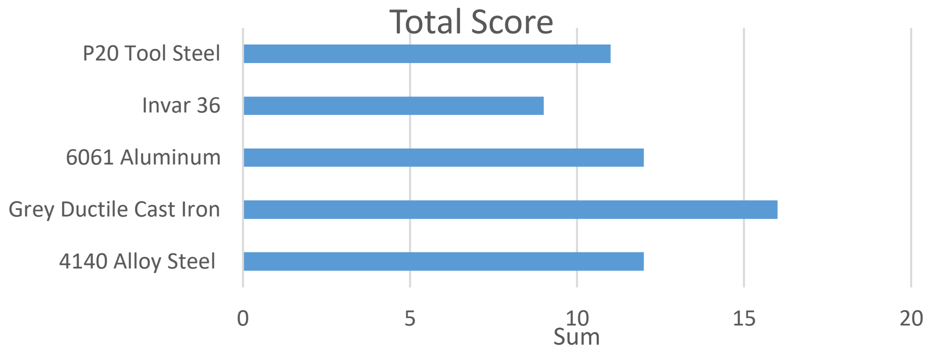


Fig. 12 Total scores of each material.

B. Microscopy

The three common materials form the material analysis 4140 alloy steel, 6061 aluminum, and grey ductile cat iron performed drastically different. When observed under microscope, the 4140 and cast iron performed similarly and showed promising results. The 6061 sample showed several defects that limit its effectiveness.

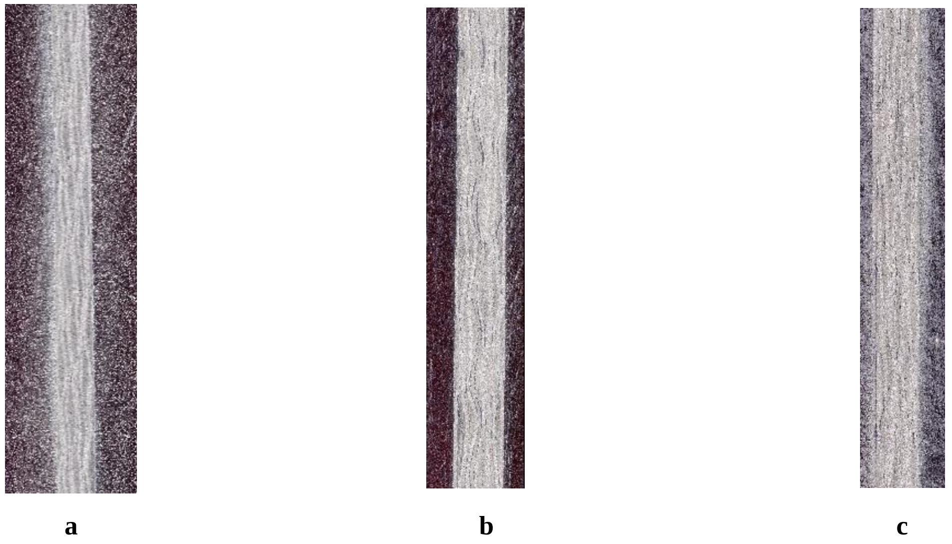
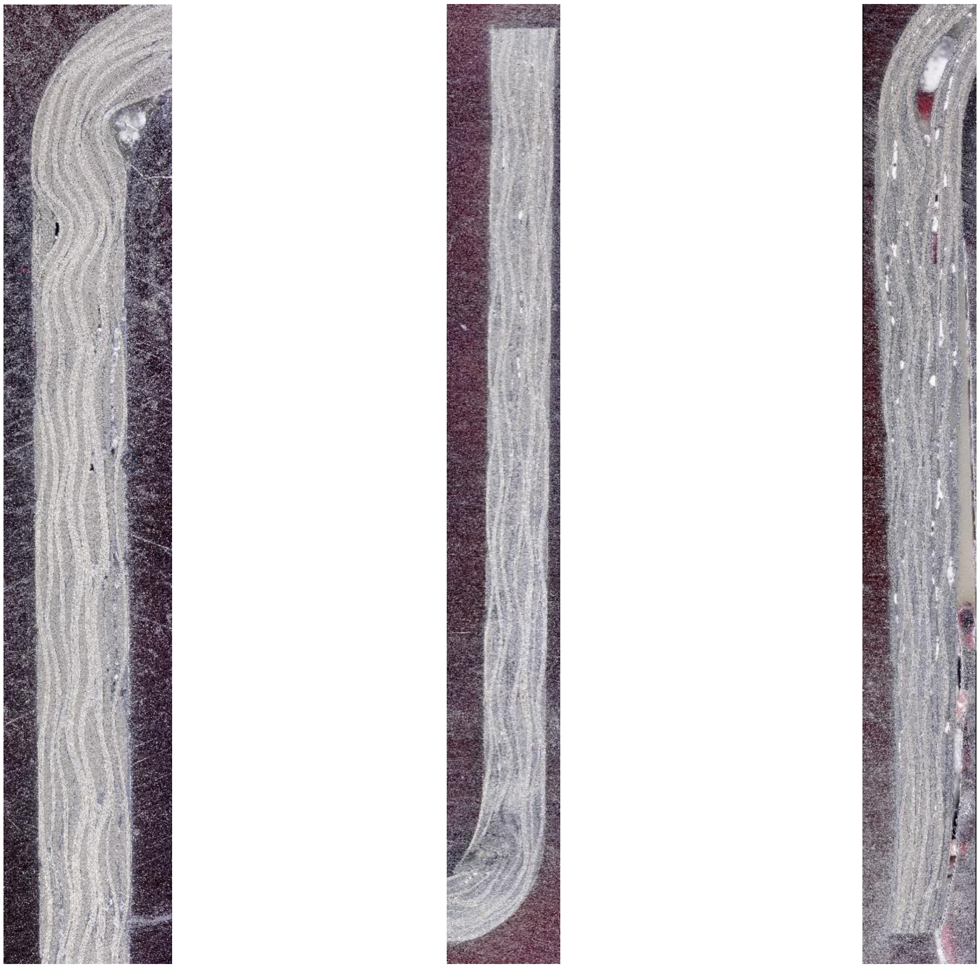


Fig. 13 C-channel webs a) alloy steel b) cast iron c) aluminum

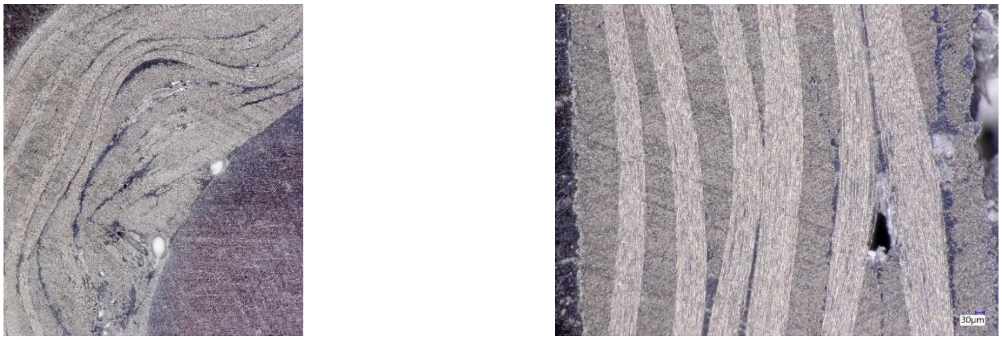
Examining the webs of the samples, all tools were able to make acceptable quality components with the aluminum tool preforming slightly better with a higher fiber volume compared to the other samples.



a b c

Fig. 14 C-channel flanges a) alloy steel b) cast iron c) aluminum

The flanges of each sample are not as consist across materials as the webs are. Both the grey ductile cast iron and the 4140 alloy steel were able to produce acceptable flanges, but the aluminum tool has numerous voids, resin overflow, and areas of low fiber volume. The 4140 and cast iron tool also have areas of concern.



a b

Fig. 15 Defects in sample a) fiber bunching in cast iron sample b) voids in alloy steel sample.

In the corners of the cast iron samples, fiber bunching is evident. This greatly diminishes the strength in the corners of these components. While not as drastic as the aluminum tool, the 4140 tool produced voids in the resin of the sample, causing localized defects in the sample.

VIII. Conclusions and Future Work

Both the 4140 alloy steel and the grey ductile cast iron show promise as materials for composite tools. Both materials have acceptable properties needed, and observations of manufactured components shows decent part quality with exception to localized defects. 6061 aluminum has limited use as a composite tooling material. Besides being the cheapest and most machinable option analyzed, its lack of performance in CTE and hardness restricted its effectiveness. Potentially, aluminum could see use in low product runs of representative components where longevity is neglected and costs are minimized, like research environments. Further work is needed to explore aluminum in this role. Also, invar 36 tooling should be compared to the 4140 and cast iron tools in order to analyze part quality with reference to industry standards. Work should also be done to show the cause of the defects in the samples shown. By knowing which property of the material is responsible for the defects. Steps can be taken to mitigate their influence on part quality or select a more suitable material option.

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