An adaptive geometry transformation and repair method for hybrid manufacturing

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ABSTRACT

Hybrid manufacturing has become particularly attractive for refurbishing of high-value freeform components. Components may experience unique geometric distortions and/or wear-driven material loss in service, which require the use of part-specific, adaptive repair strategies. The current work presents an integrated adaptive geometry transformation method for additive/subtractive hybrid manufacturing based on rigid and non-rigid registrations of parent region material and geometric interpolation of the repair region material. In this approach, rigid registration of nominal part geometry to actual part geometry is accomplished using iterative alignment of profiles in the parent material. Non-rigid registration is used to morph nominal part geometry to actual part geometry by transformation of the profile mean line. Adaptive additive and subtractive tool paths are then used to add material based on constant stock margin requirements, as well as to produce blend repairs with smooth transition between parent and repair regions. A range of part deformation conditions due to profile twist and length changes are evaluated for the case

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of a compressor blade/airfoil geometry. Accuracy of the resulting adaptive geometry transformation method were quantified by: (1) surface comparisons of actual and transformed nominal geometry and (2) blend region surface accuracy. Performance of the adaptive repair strategy relative to a naïve strategy is evaluated by consideration of material efficiency and process cycle time. It is shown that the adaptive repair strategy resulted in an increase in material efficiency by 42.2% and a decrease in process time by 17.8%, depending on the initial deformation imposed on the part geometry.

INTRODUCTION

In additive manufacturing (AM), post processing is often required to bring the component to a desired final state. Not only does each post processing step add additional cost and manufacturing time, but each step also includes significant time to transfer and setup the part between these steps. These post processing steps end up being a large contribution to the final cost of a part produced by AM [1]. Hybrid manufacturing platforms attempt to reduce these transfers and potential setup issues by combining AM processes with conventional subtractive processes in a single machine. This allows the machine to switch modalities between adding and subtracting material at any point in the overall manufacturing process. The interleaving of different manufacturing techniques allows the process to maximize the benefits of each individual method and allows for the creation of components that could not be achieved by use of either individual method in isolation [2]. Further, this allows for the rapid creation of components otherwise prohibitively expensive to manufacture in small quantities [3]. These processes also allow for the creation of small features on components that otherwise would require excessive material removal to create via subtractive processes such as flanges, fins, or bosses [4]. These advantages have prompted research in the planning and sequencing of these hybrid strategies [5, 6].

Hybrid manufacturing systems also provide the unique capability of performing component repair on worn performance components in a single machine setup. Through material buildup by additive material deposition and resurfacing by machining, worn or damaged components can be refurbished to usable conditions. This capability has become of interest to the mold and die and aerospace industries, where significant cost savings could be achieved. Parts which were once either replaced when worn or repaired by painstaking manual processes can be repaired in an automated hybrid manufacturing cell [7, 8]. Though these machines have been a topic for research for quite some time [9, 10], only recently have machine tool manufacturers introduced commercially-available hybrid systems [11]. This underscores the need for advanced process planning methods and computer-aided manufacturing (CAM) tools to support their implementation.

One application area in the aerospace industry that could greatly benefit from the implementation of hybrid manufacturing systems is the repair of airfoils such as compressor blades. While solutions from companies exist which often include proprietary equipment and software, commercial hybrid manufacturing systems eliminate the hardware barrier to entry in setting up their own repair processes, allowing for deterministic control of the entire repair process [12, 13]. In normal operation, compressor blades experience wear at their tips. This increases the clearance between the compressor and housing and decreases the efficiency of the engine [14].

These airfoil components are often repaired using a complex restoration process, shown in Fig. 1. First, the worn area is removed from the blade tip by machining. Material is then deposited on the blade using an additive process (e.g., directed energy deposition, welding). Finally, the surface is machined and blended to final form. However, final machining and blending is complicated by the fact that, during use, airfoil blades in particular may experience varying degrees of distortion. The potential variations in geometry must be considered in the final blend repair, rendering use of static toolpaths insufficient. To account for these changes, excess material is added during deposition and a safety margin is designed to be left after machining to minimize the chances of gouging the parent material. In this case, final blending of this remaining material into the parent blade material is done using a manual blending method to ensure a smooth transition between the repaired region and the original blade.

This manual hand blending process is not only time consuming and costly, but also leads to an inconsistent process and erratic final product quality due to variations in the human interaction required to complete this difficult task. However, little work has been done to fully characterize the gains (e.g., time and material savings) that could realize by implementing an adaptive repair process. Efficiency gains could be made if a fully automated process was capable of adapting to minute changes in part geometry. Previous work has investigated the use of hybrid systems which are capable of adapting on a component by component basis, however little has been stated on how to adapt the tool paths used in the repair [7, 15, 16]. In order to accomplish this, a unique set of tool paths for both the additive and subtractive phases must be generated for each unique starting geometry. This requires the model these tool paths are derived from to adapt as well, including accurate reconstruction of the remaining parent material and adaptation of the nominal tip geometry which maintains continuity with the parent surface. Qi et al. described an adaptive additive repair method for compressor blades; however only the deposition method and path is adapted, not the desired final part geometry [17]. Zheng et al. examined modeling worn areas of aerospace components [18]. However, this method did not take into account distortions that may occur in the actual blade and constructs the geometry using the nominal CAD data. A similar methodology is utilized in Piya et al. where PCS (Prominent Cross Sections) were used to reconstruct the actual geometry [19]. Yilmaz et al. demonstrated another method for compressor blade repair, however this method requires a full scan of the blade to construct the actual geometry, which requires additional setup time and digitization equipment [20]. Other presented blade reconstruction methods show promise in reverse engineering the blade geometry, but do not attempt reconstruct the geometry needed to be created in a tip repair process [21-24]. While these works have showed promise in adapting either the individual additive or subtractive phases individually, few works have shown a method applicable to all phases of the repair process. If a method were developed which could adapt the tool path for both phases of repair utilizing on machine data capture, a complete re-manufacturing process could be implemented within a commercially available hybrid manufacturing system.

This work describes a new modeling strategy for use in hybrid manufacturing systems to achieve single-machine, blend-type repairs for products with relational geometry constraints through adaption of the geometry used to derive additive and subtractive process toolpaths. A generic airfoil geometry is selected as a case example wherein geometric deformations are applied to simulate variability in starting geometry. An adaptive algorithm is proposed and evaluated wherein toolpaths for additive and subtractive processing is morphed to the initial deformations of the part geometry. In the additive phase, the algorithm constructs the additive build-up geometry based on the starting part geometry. In the subtractive phase, the algorithm employs rigid and non-rigid registration methods to reconstruct the geometry of the actual blade so to allow for adaptive tool path planning. The effects of an adaptive hybrid repair approach are evaluated and discussed based on effects on repair time and material efficiency.

ADAPTIVE REPAIR METHODOLOGY

The adaptive repair strategy is designed for implementation within the framework of an integrated additive/subtractive hybrid manufacturing machine, wherein digitization of part geometry can be accomplished utilizing common on-machine inspection (e.g., strain-gauge style inspection probes). Using this method of data capture, 2D profiles of received part geometries can be digitized, an example of which is shown in Fig. 1 for the case example of the present study – a typical compressor airfoil part. With these profiles, nominal CAD data of the component can then be manipulated to match an individual component to be repaired. This is done using a non-rigid registration method that registers and deforms the profiles of the nominal CAD data to match that of the measured part geometry. The part geometry within the repair region, in this case the airfoil tip, is then manipulated via interpolation of the previous transformations to alter the final profile of the nominal model. These final profiles can then be used to create a final solid model of the actual part to be repaired. Figure 2 shows the overall adaptive repair sequence resulting from implementation of this algorithm.

Model Digitization

The actual geometry can be captured by probing *K* cross sections of the actual component, where $K \geq 2$, at predetermined heights along the stacking axis of the profiles and outside of the repair region. The mean line of an individual profile, shown in the subset of Fig. 1, is defined as a continuous curve which lies equidistant to either side of the exterior surfaces of the component. The thickness defined as the perpendicular distance from this mean line to the edge of the blade profile. The mean line can be constructed by analyzing the center points of the minimum inscribed circles fit within the profile [25]. The probed *m* profile points at a height *z*, which are defined as a matrix of 3D coordinates $P_z = [P_0 \dots P_m]$, are first imported. A mean line, ML_z, and its assigned thickness distribution, Td_z, can be computed for the profile. The mean line is denoted as a cubic spline with a control point vector $Cp_z = [CP_0 \dots CP_n]$ and a knot vector $t_z = [t_0 \dots t_{n+4}]$, as in Eq. (1) where $N_z = [N_{0,3}(t_z) \dots N_{n,3}(t_z)]$ are the b-spline basis functions. The thickness distribution is defined as a function of the knot vector of ML_z, as in Eq. (2):

$$ML_z(t_z) = \sum_{i=0}^{n} Cp_{z,i} N_{i,3}(t_z) \quad (1)$$

$$Td_z = f(t_z) \quad (2)$$

The nominal geometry is evaluated and input using *K+1* profiles. *K* of these profiles are evaluated on the CAD at the same heights as on the actual component, while the K^{th+1} profile is evaluated at the tip of the blade. These profiles are designated as Pn_z, $MLn_z(t_z)$, $Tdn_z(t_z)$, where *n* denotes the nominal model.

Rigid Profile Registration

Alignment of the nominal CAD geometry and the actual geometry is performed using a rigid registration algorithm that translates and rotates each of the nominal profiles relative to the respective actual profiles. Due to distortion or deformation present in the actual component, each individual profile must be registered. Each nominal profile Pn_z is registered with its counterpart actual profile P_z. Doing so accounts for distortions which change the location of a profile relative to the adjacent profile, i.e. P_i relative to P_{i+1}. This rigid registration is completed using an iterative closest point (ICP) algorithm [26], which minimizes the least squared distance between the two point sets. The ICP algorithm is iterated until the decrement in error between successive iterations is less than 0.1%. The final 3 x 3 rotation matrix R and 3 x 1 translation T used in this final iteration are then stored. This operation is performed for *K* profiles on the actual geometry, yielding $R_z = [R_1 \dots R_{K-1}],\ \text{and}\ T_z = [T_1 \dots T_{K-1}]$.

The K^{th+1} profile of the nominal geometry must be transformed as well. However, no information is available regarding the K^{th+1} profile of the actual component, so an informed alignment must be calculated using the previous *K* profile transformations. In the case of *K* = 2, a linear interpolation can be made based on the data. Higher order interpolations are possible for greater values of *K*, which could lead to greater accuracy in the construction of the final model. Using only two sections, R_K and T_K can found by linear interpolation using $[R_1, R_2]$ and $[T_1, T_2]$. To calculate R_K, R_1 and R_2 must be split into their respective Euler rotation components: θ_x, θ_y, and θ_z. Reference [27] provides a method to isolate these individual components, but yields two possible solutions. The incorrect solution can be ruled out by transforming Pn_z by the calculated components and comparing the RMS error. The linear interpolation for the component rotations can then be completed according to Eqs. (3)-(5):

$$\theta_{x,3} = \frac{\theta_{x,2} - \theta_{x,1}}{z_2 - z_1} * (z_3 - z_2) + \theta_{x,2} \tag{3}$$

$$\theta_{y,3} = \frac{\theta_{y,2} - \theta_{y,1}}{z_2 - z_1} * (z_3 - z_2) + \theta_{y,2} \tag{4}$$

$$\theta_{z,3} = \frac{\theta_{z,2} - \theta_{z,1}}{z_2 - z_1} * (z_3 - z_2) + \theta_{z,2} \tag{5}$$

The rotation matrix for the K^{th+1} profile is calculated by combining the individual X, Y, and Z rotations, regardless of the order of interpolation applied, as in Eq. (6):

$$R_K = R_z(\theta_{z,K})R_y(\theta_{y,K})R_x(\theta_{x,K}) \tag{6}$$

The translation T_K is calculated similarly to R_K, based on the order of interpolation. The calculated transformations can then be applied to all *K*+1 profiles and profile mean lines by translating the profile points, Pn_z, and spline control points, Cpn_z. The transformed profiles PT_z, transformed control points CpT_z, and transformed mean lines MLT_z can be found according to Eqs. (7)-(9):

$$PT_z = R_z Pn_z + T_z \tag{7}$$

$$CpT_z = R_z Cpn_z + T_z \tag{8}$$

$$MLT_z(t_z) = \sum_{i=0}^{n} CpT_{z,i} N_{i,3}(t_z) \tag{9}$$

This rigid registration is capable of aligning the two data sets in 3D space, as well as capturing any changes between profiles such as blade twist. Twist (θ), shown in Fig. 3(a), is defined here is defined as planar rotation of a profile about the radial axis of the blade.

Mean Line Registration

Deviations in mean lines are addressed by comparison of the mean lines for the actual and nominal geometry, ML_z and MLT_z. The form of these mean lines can be compared by examining the spline control points. The deviations between corresponding control points can be defined as D_z. Similar to the rigid registration, the *K*th mean line is also manipulated via an interpolation function. For this case of *K* = 3, this is done using a linear interpolation on a control point by control point basis. The adapted nominal control points for each spline can then be calculated as in Eq. (10):

$$Cpf_z = CpT_z + D_z \tag{10}$$

Then, the final mean lines MLF_z can be calculated as in Eq. (11):

$$MLF_z(t_z) = \sum_{i=0}^{n} Cpf_{z,i} N_{i,3}(t_z) \tag{11}$$

By using this mean line registration, the algorithm is capable of capturing any variation in the form of an individual profile. An example of this is a compression of the blade within the profile plane, this resulting in a change in chord length (*ΔC*). This is type of deformation is shown in Fig. 3(b).

Profile Creation

After the mean lines have been manipulated, the final blade profiles can be generated by assessing the profile thickness distribution along corresponding profile mean lines. Points are then projected perpendicular to the curve. First, the mean line derivatives MLF_z' are calculated. Using these derivatives, vectors perpendicular to the curve, defined as $N_z(t)$, can be calculated within the XY plane and normalized. To create the final profile PF_z, points are then placed on either side of the final mean line MLF_z at a distance Td_z along the normal vector N_z. The actual thickness distribution Td_z is used to evaluate the final profiles for the non-repair region, while the nominal thickness distribution is used for evaluating the final profiles for the K^{th} profile. The final profiles for each contour (e.g., *z* = 1,..,*K+1*) are evaluated using general form as in Eq. (12):

$$PF_z = MLF_z(t) \pm Td_z(t)N_z(t) \tag{12}$$

The final solid model can then be created by lofting the individual profiles.

RESULTS

For the purpose of model validation, a representative nominal model geometry was created from a pre-defined mean line and thickness distribution. These three profiles were then lofted to create a final solid model. Simulation of deformations to the nominal model were made by introducing both twist and chord length changes, both of which are expected conditions of serviced airfoil geometry. Twist in the blade was created by rotating the blade profiles about the blade radial axis, while chord manipulations were created by modifying the profile mean line for the individual sections. Chord length changes were made by translating the tips of the blade at controlled distances, while the profile mean line bowed or stretched in order to preserve the arc length of the curve. Twist applied to the blade varied between ±0.1180 deg/mm in increments of 0.0394 deg/mm and chord length changes varied between $\pm 2.28 \times 10^{-3}$ mm/mm in increments of 1.14e-3 mm/mm.

An actual (deformed) blade with $\theta = -0.1180$ deg/mm, $\Delta C = -2.28 \times 10^{-3}$ mm/mm was generated to first test the algorithm. Figure 4(a) shows models for both the actual blade (in red) and nominal model (in grey). The resulting transformation result is shown in Fig. 4(b). The profiles are first rigidly transformed and registered using the ICP algorithm, which acts to minimize the overall distance between a nominal profile and its corresponding actual profile. The transformation of the final profile in the repair region is then interpolated based on the transformed profiles for the non-repair region. Figure 4(b) shows the two models after rigid transformation. While the profiles have been roughly aligned in space to one another, some deviation remains between the two profiles, mainly in the center of the blade where chord compression has bowed the profile mean line. Figure 4(c) shows the model after final manipulation of the mean line, which should match the nominal mean lines to the corresponding mean line on the actual model.

Figure 5 displays and example of one of these comparisons. A deformed blade with $\theta = -0.1180$ deg/mm, $\Delta C = 2.28 \times 10^{-3}$ mm/mm is initially shown compared to the nominal model. After the algorithm is complete, a surface comparison is performed on the two models by measuring the magnitude of deviation from the actual model. Figure 5(b) shows the surface comparison of the actual blade and the final output of the algorithm. Positive deviations describe regions in which the deformed nominal lies outside, or is larger than, the intended actual geometry, while negative values indicate regions which lie within, or are smaller than, the intended actual blade geometry. The largest deviation between the two models is 15.5μm, located at the tip of the blade. This is where the largest deviation is expected to be, as the deformation of this profile is a product of interpolation. The mean deviation of the two surfaces reported is 0.07 µm, with a standard deviation of 1.6 µm. This deviation is likely driven primarily by generation of the underlying .stl files, which were created with a tolerance of 5μm.

The surface comparison results for three other samples with θ values of ±0.1180 deg/mm and ΔC values of ±2.28 x 10^{-3} mm/mm can be seen in Table 1. A mean deviation of 0.065 µm across all samples was found, confirming the model validity for the majority of the blade geometry. The maximum profile deviation of 15.5 µm was observed for a deformation condition of θ = -0.1180 deg/mm, ΔC = 2.28 x 10^{-3} mm/mm, which were the extremum for deformations examined. The location of the maximum profile deviation occurred in the repair region for all deformation conditions. This is generally expected, as the third profile’s transformations are computed via interpolation from the profiles in the non-repair region. The overall impact on the blend process is minimal, however, as this is not critical to the interface between the repair region and parent (non-repair) region surfaces.

During the part repair process, the repaired region needs to be constructed, and has no reference to the original part geometry. Therefore, it is imperative that the algorithm accurately reconstruct the geometry where the parent region meets the repaired region material. To test this, additively repaired geometries were created for the maximum conditions observed in this study; ±0.1180 deg/mm and ΔC values of ±2.28 x 10^{-3} mm/mm. The repair algorithm was used to transform the nominal geometries and a surface comparison was then performed to analyze the differences between registered regions. Figure 6 demonstrates the results for one deformation condition with geometric deformation parameters of $\theta = -0.1180$ deg/mm, $\Delta C = -2.28 \times 10^{-3}$ mm/mm. The maximum deviation for this region was found to be 3.36 µm and occurred at the base of the repair region interface with the parent material. The location of this maximum deviation is expected, as any geometry created past the K^{th} probed section is highly dependent on the interpolated final profile. Further, the surface comparison in Fig. 6 yielded a maximum deviation which fell within the tolerance for .stl generation.

DISCUSSION

The previous results have shown that this algorithm is capable of accurately manipulating the CAD geometry of a nominal model to match the geometry of a part that has experienced deformation in service. In use, this algorithm could be used to create models of the actual blade for use in both the additive and subtractive phases of the repair process.

In during a tip repair, the damaged blade tip is first removed from the blade via machining. Material is then deposited using a welding process to rebuild the removed material. This is completed using a predetermined path derived from the nominal CAD geometry of the blade. However, due to variations in blade geometry associated with deformation in service, this static path may be ineffective as: (1) it may not provide sufficient material to successfully complete the machining phases of the repair, (2) it may be inefficient in terms of material efficiency. The effects of the former case are shown in Fig. 8(a), where the deposition path did not provide adequate margin of material between the weld and the intended final part geometry. This can be mitigated by increasing the thickness of the deposited bead along the nominal path. However, such a naïve approach would introduce uneven margin of material between the deposited weld and the intended final part geometry. This material inefficiency is evident in Fig. 8(b). In this regard, adaptation of the repair geometry could be made following the transformation algorithm described above. Figure 8(c) shows the result in the case where the repair geometry for each blade is adapted using the previously described algorithm with a set margin allowance.

To determine the potential material savings using an adaptive additive repair method, 35 actual blade models were created using θ = [-0.1180, -0.0787, -0.0394, 0.0000, 0.0394, 0.0787, 0.1180] deg/ mm and ΔC = [-2.28×10^{-3}, -1.14×10^{-3}, 0.00, 1.14×10^{-3}, 2.28×10^{-3}] mm/mm. Each model was input into the algorithm to create a deformed nominal model for each. Adaptive weld geometries for each sample were created by adding a margin of 1.27 mm to the thickness distribution of each blade during the profile creation process to allow an adequate margin for the subsequent machining process. These surfaces were then trimmed at consistent heights, closed with planar surfaces, and filleted to create solid geometries. Non-adaptive blades were then created by increasing the thickness of the nominal weld until the minimum distance between the weld and intended part geometry reached the required margin of 1.27 mm.

For each sample, a material efficiency was calculated by dividing the nominal weld volume by the samples respective volume for both the adaptive and non-adaptive weld generation process. Figure 8 shows the material efficiency compared to the nominal weld volume for all samples. As expected, more weld volume is required during the non-adaptive process as the actual blade geometry varies increasingly farther from the nominal blade. From the figure, both types of geometry changes (twist and chord length) have an effect on the material efficiency of the weld deposition, however blade twist has a much more significant effect for the values in the present study. At its maximum value of $\Delta C = 2.28 \times 10^{-3}$ mm/mm, changes in chord length alone only saw a decrease in efficiency of 3.6%. This is compared to a 42.2% decrease in efficiency seen in a model with the maximum value of twist $\theta = 0.1180$ deg/mm. In comparison, the material efficiency of the adaptive process remains very close to 100% for all samples. In fact, the lowest efficiency recorded in the adaptive process was 99.2%, which occurred at a $\theta = -0.1180$ deg/mm and $\Delta C = -2.28 \times 10^{-3}$ mm/mm.

The non-adaptive deposition strategy not only affects material efficiency for additive processing, but also for the subsequent machining process. To evaluate these effects, the difference in required machining time between the adaptive and non-adaptive deposition strategies was investigated. The primary differences between the two are in the time required to remove excess material from the repair geometry. Figure 9 shows the steps taken in the machining simulations. This involves the following elements: a 3-axis roughing pass to intermediate geometry, a pre-finishing pass utilizing 5-axis toolpaths to reduce the repair region to a uniform margin, and a final finishing pass utilizing 5-axis toolpaths to bring the part geometry to its final state.

The machining parameters and tools associated with each of these toolpaths are shown in Table 2, and are common parameters for machining Inconel 718, a common airfoil alloy [28]. For each sample, the time required to complete each machining operation was recorded, along with the volume of material removed during the operation. Table 3 shows the results from a sample generated with parameters $\theta = -0.1180$ deg/mm, $\Delta C = -2.28 \times 10^{-3}$ mm/mm. The adaptive additive repair and adaptive machining strategy shows a significant improvement of 12.23 minutes in the process machining time. Table 3 also shows the material volume removed between the two repair strategies, and which individual steps in the process see the greatest change in material removal. From the table, while the process times for the pre-finish and finish passes remain unchanged, the roughing process sees a significant increase of 12.22 minutes. This directly shows the time required to process the excess material deposited during the non-adaptive deposition strategy. The roughing pass also shows the largest change in volume of material removed. However, the pre-finishing tool path also shows an increase in material removed. This is due to an increase in material lying under overhanging regions which are inaccessible to the three-axis roughing process. This excess material must then be removed in the 5-axis pre-finishing process. As expected, the finishing process sees no change in either machining time or material removed.

These machining simulations were completed on 10 separate samples with varying levels twist and chord change. Table 4 shows the total change in machining time to removed welds created in the adaptive and non-adaptive weld deposition strategies. For each of the samples tested, significant decreases in the machining time were realized as a result of the adaptive weld deposition strategy. A minimum of 9 minutes of machining time was reduced from all samples, which is approximately a 10% decrease in machining time for this process. The maximum reduction in machining time was 16.17 minutes, which is a decrease of 17.8% for this particular sample.

CONCLUSIONS

In this work, a method for adaptive geometry transformation which could be implemented in a single setup for hybrid manufacturing machines was presented. This method utilized data from on machine inspection systems to manipulate the nominal CAD geometry to match an individual blade in need of repair. The manipulated CAD data was shown to match the actual blade in simulations with a maximum deviation of 15.5 µm, occurring in the repair region of the part. However, in the case of blending for a blade repair, the maximum deviation seen in the transition region between the manipulated CAD and the actual blade was shown to be only 3.6 µm. By utilizing this adaptive method in a commercial hybrid manufacturing system with control over both the additive and subtractive phases of the process, significant process savings can be realized. These savings have been shown not only in material savings in the deposition phase, but also in process time in the finish machining stage. Using adaptive strategies such as this, smart repair strategies can be developed which better utilize the full capability of these new manufacturing capabilities. Future work will include optimization of data acquisition, design and adaptation of additive tool paths, a data exchange framework, and implementation on a commercial hybrid machine.

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Table Caption List

Figure Captions List

Fig. 8 Comparison of adaptive (a.) and non-adaptive (b.) material efficiency in the weld deposition process with respect to changes in Twist (θ) and Chord compression (ΔC)

Fig. 9 Images of tool path strategies used in machining simulations, roughing (a.), pre-finishing (b.), and finishing (c.), and their resulting geometries (d), (e.), (f.), and (g.)

Sample	Max. (μm)	Min. (μm)	Mean (μm)	σ (μm)
$\theta = -0.1180$, $\Delta C = 2.28 \times 10^{-3}$	15.48	5.48	0.07	1.58
$\theta = -0.1180$, $\Delta C = -2.28 \times 10^{-3}$	12.32	9.20	0.04	1.99
$\theta = 0.1180$, $\Delta C = -2.28 \times 10^{-3}$	6.38	7.49	0.10	1.85
$\theta = 0.1180$, $\Delta C = 2.28 \times 10^{-3}$	6.49	6.38	0.05	1.53
Average	10.17	7.14	0.065	1.74

	Roughing	Finishing
Tool	6 Flute, 12.7 mm End Mill	4 Flute, 12.7 mm Ball Mill
Speed (SMM)	60.96	60.96
Feed (mm/Tooth)	0.0254	0.0254
Stepover (mm)	1.27	0.254
Stepdown (mm)	2.54	-

	Adaptive Repair		Non-Adaptive Repair	
	Machining Time (min)	Volume Removed (mm^3)	Machining Time (min)	Volume Removed (mm^3)
Roughing	10.13	783.96	22.35	2515.91
Pre-Finish	31.73	181.90	31.73	203.20
Finish	30.83	397.22	30.83	397.88
Total	72.70	1363.08	84.93	3116.98
Delta	-	-	12.23	1753.91

	θ (deg/mm)				
ΔC (mm/mm)	-0.1180	-0.0394	0	0.0394	0.1180
-2.28×10^{-3}	12.23				14.58
-1.14×10^{-3}		12.17		16.17	
0	12.00		0		12.55
1.14×10^{-3}		10.12		10.93	
2.28×10^{-3}	9.77				13.82