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Machining Strategy Development in 5-Axis Milling Operations Using Process Models

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Abstract
Increased productivity and part quality can be achieved by selecting machining strategies and conditions properly. At one extreme very high speed and feed rate with small depth of cut can be used for high productivity whereas deep cuts accompanied with slow speeds and feeds may also provide increased material removal rates in some cases. In this study, it is shown that process models are useful tools to simulate and compare alternative strategies for machining of a part. 5-axis milling of turbine engine compressors made out of titanium alloys is used as the case study where strategies such as flank milling (deep cuts), point milling (light cuts) and stripe milling (medium depths) are compared in terms of process time by considering chatter stability, surface finish and tool deflections.

Keywords: Five Axis Milling, Machining Strategy, Process Modeling

1. Introduction

With the increasing demand for performance designs, mechanical components having complex geometries and surfaces are required to be manufactured in tight tolerances. In manufacturing of high performance designs, the complex part surface must be generated maintaining the dimensional and tolerance integrity with minimized number of setups which requires tool positioning and contouring capability. Five axis milling, where the tool has two additional rotational degrees of freedom, meets this requirement. Due to these advantages, five axis milling has been widely utilized in aerospace, automotive and die-mold industries. Increased productivity is of great importance in such industries due to the high cost of the machine tool, equipment and the raw material involved.

Selection of the machining strategy has a very crucial role in achieving this aim, and can be considered in two main stages; the global and local strategy. The former is related to selection of the approach for material removal whereas the latter considers process parameters used in the tool path. For example, in case of machining of turbine engine compressors, there are several global strategies such as flank milling, point milling and plunge milling, whereas some of the local strategies are zig, zig-zag, helical, raster and trochoidal. The required configuration and specifications of the machine tool, the required cutting tools to be utilized in the process and overall productivity depend on the selected global strategy, as well. Therefore, the process planner should decide on the right strategy for the part under interest. However, this is not a straight forward task as several aspects such as geometry, mechanics and dynamics of the process, and the nonlinear relation between them, should be taken into account. For five axis milling applications there have been several approaches [1-8]. Several authors investigated the effects of toolpath pattern on the process, [9,10]. Most of the studies on machining strategy selection are concentrated on the tool trajectory where cutting forces, tool deflections and maximum feed rate maps are utilized to decide tool feed direction and select the best toolpath pattern [9,10].

There have been considerable amount of work in stability of 3-axis flat-end milling. In one of these, the stability of 3-axis flat-end milling stability was formulated by Budak and Altintas [11]. This formulation was later applied to 3-axis ball-end milling by Altintas et al.[1]. The literature in 5-axis milling stability, on the other hand, is limited Khachan and Ismail [2] applied time-domain approach to multi-axis milling, but they verified their model only by 3-axis milling tests. Ozturk and Budak [3] formulated 5-axis ball-end milling stability using single and multi-frequency solution methods. Budak et al. [4] showed the effect of both lead and tilt angles on stability limits. Shamoto and Akazawa [5] also modeled the stability of 5-axis ball-end milling; however they only demonstrated the effect sof the tilt angle.

Several researches studied tool workpiece engagement to cutting force calculations in multi-axis milling. Kaymakci et al. [6] presented a model where a uniform 3D point cloud is used to approximate the workpiece geometry. The tool path is divided into short segments of 5 axis sweep motions. The engagement entry and exit angles at each height along tool axis are calculated. Stautner [7] used a 3 folded nail block model, where the nails are aligned along the main process directions, i.e. x, y and z. The intersection points of tool sweep with nails are used to calculate the forces directly.

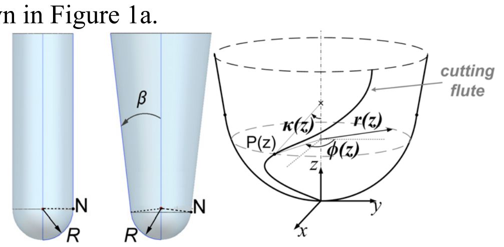
In this study, previously developed process models [3,4,8,12,13,15] are used in an integrated manner for machining strategy development in 5-axis milling. The possible global machining strategies for a given part are compared in terms of cycle time and part quality, considering the cutting mechanics and dynamics of both machine tool system and the in-process workpiece (IPW). The cutting forces and resulting deflections in ball end milling are calculated using the force model presented by Ozturk and Budak [8]. The stability limit at low cutting speeds under the effect of process damping is estimated by extending the model presented by Budak and Tunc [12] to ball end milling. The five axis ball end stability model developed by Ozturk and Budak [3] is used in estimation of stability limits at high cutting speeds. The geometric interaction between the cutting tool and workpiece, throughout a cutting pass is identified using the geometrical calculation procedure provided by ModuleWorks®. The dynamics of the in process workpiece IPW is estimated using the methodology developed by Alan et al. [13].

The paper is organized as follows. In the next section the process geometry for ball end milling and taper ball end milling are given briefly. Then, the considerations in strategy development and comparison are discussed in section 3. After describing the theoretical background on process modeling in section 4, the application of the proposed methodology is discussed on sample production parts and conclusions are derived.

2. Geometry of Five Axis Milling

2.1. Geometry of general ball end mills

Ball end mills are widely used in multi-axis machining where spherical tip of the tool provides high contouring capability to machine free form and sculptured surfaces. In general, ball end mills consist of a spherical tip with radius R and a straight or conical body with taper angle β as shown in Figure 1a.



(a) Types and (b) Geometry of general ball end mills.

Figure 1: General tools with spherical end.

Every point on the cutting flutes is represented in cylindrical coordinates designated by local radius r*(z),* axial immersion angle $\kappa(z)$ and radial immersion angle $\phi(z)$in Figure 1b. Thus, a discretized 3D frame consisting of the envelope points is constructed and the tool is represented as circular discs at each elevation in z axis.

Tapered ball end mill helical flutes can be ground in two different ways; constant helix and constant lead. Constant helix tools have same helix angle, i_o along a flute whereas constant lead tools have constant pitch length along the flute at the conical or flat body where helix angle can vary due to the taper angle. Helix angle introduces lag to the cutting points at different axial levels with respect to previous points on the flute. Total immersion angle for a point on the flute edge is defined as the combination of immersion angle due to rotation, $\phi(z)$ and lag angle at the specified elevation, $\psi(z)$ as follows:

$$\phi_j\left(z\right) = \phi + \phi_{p_j} - \psi(z) \quad (1)$$

Lag angle definition differs along the flute due to complex cutter body geometry. Engin and Altintas [14] constructed an analytical lag angle definition for general end mills and in this paper their model is simplified to cover general ball end mill geometries. A rotational transformation is applied to the cutter geometry with respect to the lead and tilt angles [15] in order to perform required coordinate transformations.

3. Considerations in Strategy Selection

In general, the design geometry is machined from the blank geometry in three main stages such as roughing (R), semi finishing (SF) and finishing (F). Mostly, roughing and finishing stages consist of single step. However, it may be required to apply multiple steps in semi finishing stage to satisfy the desired dimensional tolerances, depending on the applied global strategy. Moreover, different constraints may limit the process and various considerations need to be taken into account as summarized in Table 1. The required spindle torque, spindle power and axis speed limits of the machine tool also affect on the selected strategy.

Table 1: Considerations in strategy selection.

	Roughing	Semi Finishing	Finishing
Objective	Fast Removal	Constant Stock	Design Geometry
Tolerances	Loose	Tight	Very Tight
Chip Load	High	Medium	Low
Dynamics	Tool	Tool &Work	Tool &Work
Deflection	Tool	Tool &Work	Tool &Work

The objective of the roughing stage is removing the unwanted volume as quickly as possible. Thus, the chip load on the cutting tool and resulting cutting forces, torque and power are high. The process specific geometrical tolerances are loose with respect to semi finishing and finishing. However, excessive amount of stock left from roughing will be removed in the following stages. Therefore, the uniformity of the stock left on the workpiece is also an important criterion for roughing. In general, during roughing the workpiece is usually more rigid with respect to the cutting tool. In such cases, the tool flexibility determines the process stability and the form errors.

Semi finishing is applied to achieve uniform constant stock on the design geometry, prior to finishing. Therefore, the geometrical tolerances are tighter with respect to roughing. On the other hand, higher cutting speeds can be utilized as the contact time per revolution is shorter, allowing higher cutting speed and requiring higher linear feed rates. The chip load is usually smaller with respect to roughing, therefore the required cutting force, torque and power decreases drastically in those cycles. In this respect, the machine tool is required to have faster axis speeds rather than a powerful spindle. The tolerance on the tool deflections is tighter in order to keep uniformity on the left stock. Depending on the left stock and the workpiece geometry, structure of the in-process workpiece may contribute to the process dynamics and form errors as well.

Obtaining the design geometry and surface quality is the most important objective of the finishing stage. In this respect, chatter vibrations must be avoided and form errors must be kept within tolerances. If the design geometry consists of thin walled structure, the workpiece may contribute to process dynamics and form errors, which should be kept within tolerances. The amount of stock left from the semi finishing stage is one of the most important parameters affecting the tool/workpiece deflections and vibrations. The chatter stability also depends on the number of cutting passes, as well. On the other hand, the height of the scallops left on the workpiece surface should not exceed the required surface quality. Therefore, the surface quality is another constraint on the number of cutting passes. The tool-workpiece contact time per revolution is much shorter allowing higher cutting speeds.

4. Process Modeling

4.1. Modeling of cutting forces

The differential cutting forces acting on the infinitesimal elements on the flutes are calculated using oblique cutting mechanics [16]. The mechanistic force model represented in [17] is utilized and extended to calculate the forces in multi-axis general ball end milling (see Figure 2)

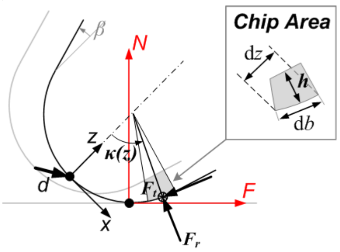


Figure 2: Differential cutting forces and chip area.

4.2. Tool workpiece engagement model

Simulation of material removal is performed by many commercial CAD/CAM systems. Though, the result is a graphical display of the remaining part after the operation or a 3D facet model, however the engagement information between the tool and workpiece is not provided.

In this study, the tool-workpiece engagement model, developed by Moduleworks® is utilized similar to the approach in some previous works [6][10]. A 3-folded nail block is used to represent the workpiece, where the tool motion is broken into short segments. The nail block model is updated by the intersection of tool swept volume with the nail block model, where a nail can be shortened, removed or split into sub nails. The tool is dicretized into number of discs along the tool axis. The intersection points are mapped on the surface of each disc (see Figure 3).

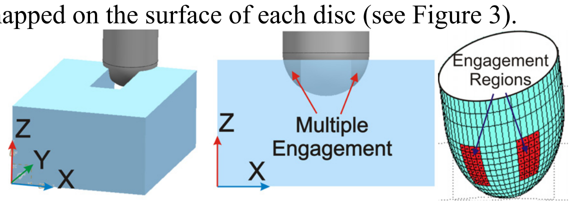


Figure 3: Multiple engagement intervals.

Each intersection point is projected to an interval at the surface area of the disc. The engagement interval covered by a given intersection is calculated by Δα in radians = grid distance / R, where R is the radius of the disc. The union of all engagement intervals gives as a result the list of disjoint engagement intervals for the disc. Further, this approach allows engagement angle calculation within the range of 0 and 360 degrees and allows detection of multiple engagement regions (Figure 3), as well.

4.3. Structural model of in process workpiece

The structural flexibility of the in-process workpiece (IPW) may be dominant at semi finishing and finishing stages if the design geometry consists of thin walled structures, such as fins or turbine discs. Under such circumstances the stability limits may change throughout the machining cycle as material is removed from the workpiece. Different steps for machining of a plate like geometry are given in Figure 4 [13].

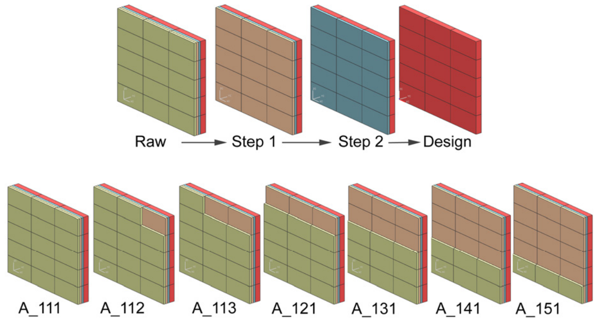


Figure 4: Different machining steps of a plate geometry.

The variation of the frequency response function (FRF) and stability diagram of such a geometry for different steps are given in Figure 5a and Figure 5b, respectively [13]. It is clearly seen the stability of the process changes drastically as material is removed from the workpiece. Therefore, the dynamics and structural stiffness of the IPW needs to be estimated.

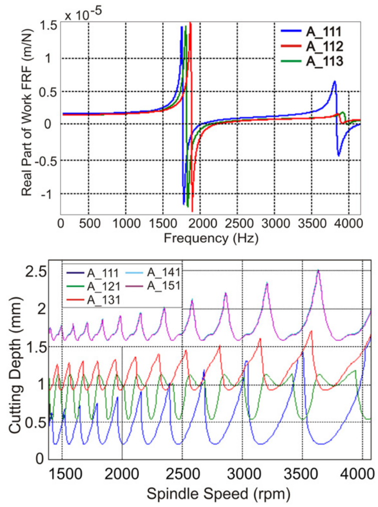


Figure 5: Variation in the FRF of IPW and stability lobes.

For such a purpose structural modification method with additional degrees of freedom [13] is used in this study. The procedure is based on the matrix inversion method, which is an FRF-based structural modification technique [18]. The FRFs of the in process workpiece is calculated using the FRFs of the design geometry and the dynamic structural matrix of the removed material, as follows [13]:

$$[\gamma]=\left[\left[[K]+[\Delta K]\right]-\omega^2\left[[M]+[\Delta M]\right]+i\left[[H]+[\Delta H]\right]\right]^{-1} \quad (2)$$

where, $[M]$, $[H]$ and $[K]$ are the mass, structural damping, and stiffness matrices of the design geometry and

$[\Delta M]$, $[\Delta H]$ and $[\Delta K]$ are the modification matrices to the original structure, respectively. The FRF of the part at different stages is estimated based on the FRF of the design part obtained by FEA. The whole procedure is divided into three steps: 1) geometric and FEA modeling 2) modal analysis and FRF extraction 3) structural modification with the removed material. Then, the predicted FRFs are coupled with the tool FRF to predict the stability diagrams.

4.4. Stability model

In this paper, stability model developed for 5-axis ball-end milling is used. In the model [3], the variations of engagement zones and cutting conditions along the tool axis are considered by dividing the tool into disc elements with thickness of Δz (Figure 6). The dynamic cutting forces in x, y and z directions for reference immersion angle φ on a disc element l is calculated as follows:

$$\left[F_x^{\,l}(\varphi) \quad F_y^{\,l}(\varphi) \quad F_z^{\,l}(\varphi) \right]^T = \Delta a \boldsymbol{B}^l(\varphi)\boldsymbol{d} \qquad (3)$$

where Δa is the height of the disc elements in surface normal direction, $\boldsymbol{B}^l(\varphi)$ is the l^{th} disc's directional coefficient matrix at the reference immersion angle φ [3]. $\boldsymbol{d}$ is the dynamic displacement vector which can be expressed as the difference between relative displacements of tool with respect to workpiece at current time and one tooth period before:

$$\boldsymbol{d} = \left[x(t) - x(t-\tau) \quad y(t) - y(t-\tau) \quad z(t) - z(t-\tau) \right]^T \qquad (4)$$

where τ is the tooth period. Skipping some intermediate steps which are presented in [3] in detail, the following eigenvalue problem is obtained:

$$[\boldsymbol{F}]e^{i\omega_c t} = \Delta a(1 - e^{-i\omega_c \tau})\left(\sum_{l=1}^{m} \boldsymbol{B_o}^l \right)[\boldsymbol{G}(i\omega_c)][\boldsymbol{F}]e^{i\omega_c t} \qquad (5)$$

In (5), ω_c is the chatter frequency, $\boldsymbol{G}$ is the transfer function matrix of the summation of tool and workpiece dynamics and m is the number of disc elements in the analysis. Since the number of disc elements to be included in the analysis is not known, stability diagrams are obtained using an iterative procedure.

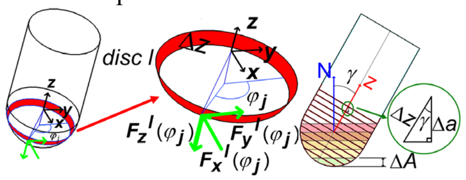


Figure 6: Dynamic forces on the disc element l

5. Process simulation for strategy selection

There can be several general machining strategies depending on the combinations of cutting speed and cutting load. In flank milling very high cutting depths are used whereas in stripe milling, the whole height of the workpiece is divided into a several passes representing a medium-depth case. In point milling, on the other hand, the tip of the cutting tool traverses the workpiece surface removing small depths (see Figure 7). These three strategies are considered to represent high, medium and low depth processes. There can also be other strategies utilizing specialized tool geometries as well. Process simulation is used to compare various machining strategies in terms of cycle time considering the previously mentioned issues, which is done in the following manner. First, the available process types for each stage are identified. Then, the feasible combinations of these operation types are generated for each stage. Note that, the selected set of parameters for the current stage depends on the currently and previously selected operation types. For instance, for a specific application, in the roughing stage flank, stripe or point milling, and at the semi finishing stage point milling can be applied. Since the stock left from the roughing stage by flank milling and point milling would be different, so would the parameters for point milling at the semi finishing stage. The procedure and the named strategies are shown in Figure 7.

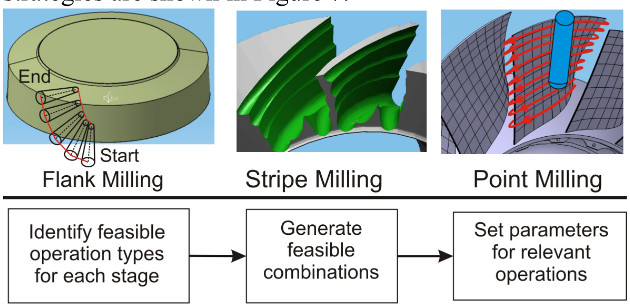


Figure 7: Comparison of machining strategies.

The machining parameter sets for each stage are selected using process models subject to the process constraints. Finally, process simulation is performed for each operation's candidate strategies. By use of such an approach the advantages and disadvantages of each type of operation can be observed for a given workpiece geometry. Since the parameter set for a given type of operation is chosen considering also the operation type selected at the previous stage, the cross effects of the operations selected at different stages can be observed, as well.

6. Applications

The developed models and procedure are applied on machining of a compressor disc made of Ti6Al4V, which is shown in Figure 8. There are 14 blades on the geometry and the angle between the blades is about 26 degrees, which is considered in selection of the diameter and taper angle of the cutting tools.

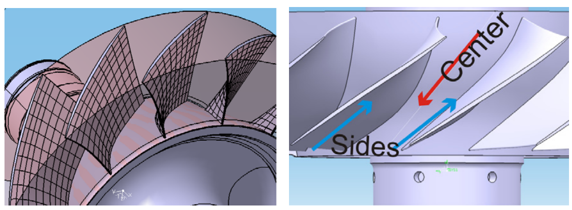


Figure 8: The example workpiece geometry.

The blades consist of arbitrary surfaces, which have more than one degree, i.e. the blades have twisted geometry in both –u and –v directions. Considering that the cutting tools have linear envelopes both flank milling (FM) and stripe milling (SM) fails to generate the design geometry. Thus, they are not suitable for finishing (F) for this geometry. However, they can be applied in the roughing

(R) and semi finishing (SF) stages, possibly requiring multi semi finishing passes. On the other hand, point milling (PM) has much more contouring capability. Thus, it is suitable for all stages.

6.1. Strategies

Three representative combinations of these operations are applied as individual strategies as listed in Table 2. However, the number of candidate strategies can be increased by using different combinations of operation types for each side of the blades, as well. The requirement for multi pass semi finishing is determined considering the variation of the stock amount left from the roughing stage and the corresponding tool deflection. In selection of the cutting tools, the workpiece geometry and the related operations are taken into account. For flank and stripe milling taper ball end mills with 3 cutting flutes, 12 mm of tip diameter and 5 degrees of taper angle (tool 1), for point milling straight ball end mills with 14 mm of diameter and 4 cutting flutes (tool 2) are used, respectively.

Table 2: The compared strategies.

	R	SF	F
ST 1	FM Center	PM Sides	PM Around Blades
ST 2	PM Sides	PM Sides	PM Around blades
ST 3	SM Sides	PM Sides	PM Around blades

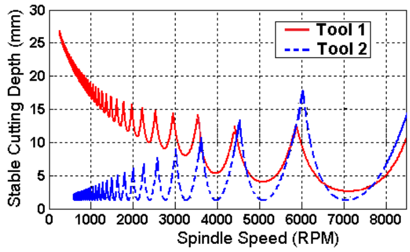
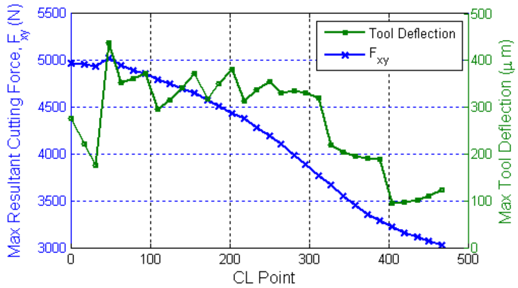


Figure 9: Stability diagrams for slotting case.

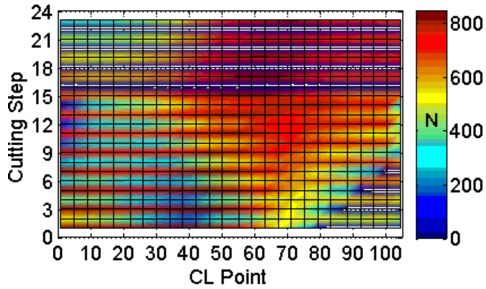
Table 3: Machining parameters.

		Spindle Speed (rpm)	Feed per tooth (mm/rev)	Cutting Depth (mm)	Step Over (%)
ST1	R	500	0.03	60	100
	SF	1950	0.1	4	25-50
	F	10000	0.05	0.05	4
ST2	R	1950	0.075	1.5	100
	SF	1950	0.1	4	10
	F	10000	0.05	0.05	4
ST3	R	1000	0.05	15	100
	SF	1950	0.1	4	10
	F	10000	0.05	0.05	4

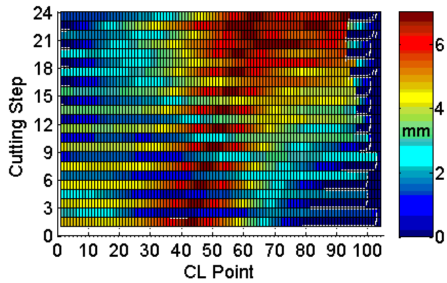
The stability diagrams for slotting case using tool 1 and tool 2 are shown in Figure 9, respectively. The effect of process damping is also considered for tool 1, which is used for flank and stripe milling. This is done by estimating the interference volume between the tool's flank and the workpiece for one revolution of the cutter [12]. From Figure 9 it is seen that for spindle speeds below 2000 rpm, the stable cutting depth increases drastically. Since relatively higher cutting speeds and lower cutting depths are utilized in point milling, the effect of process damping on stability is not considered, as shown in Figure 9. The selected process parameters for each operation are given in Table 3. The finishing parameters are chosen according to surface quality and the stability diagrams generated considering the workpiece dynamics before the finishing stage, where 0.5 mm of stock material is left to the finishing stage.



(a) Cutting forces in roughing



(b) Cutting forces in semi finishing.



(c) Amount of stock left from roughing pass.

Figure 10: Simulation and stock left from roughing.

6.2. Simulations

The resultant transversal cutting force on the tool and the max tool deflection are simulated with the selected process parameters for the roughing and semi finishing passes as shown in Figure 10a and b, respectively. The variation of the stock left from flank milling at the semi finishing stage is shown in Figure 10c, as well. It is clearly seen from Figure 10c that, the single pass flank milling of the center leaves an excessive and highly varying stock on the workpiece, which results in highly varying cutting forces in the semi finishing pass. For such cases, multi pass semi finishing needs to be applied in order to leave uniform stock to the finishing stage. Therefore, for strategy 1 the semi finishing is performed in two passes. The process parameters are also determined in a similar way for the other strategies. The comparison of the machining time resulting from each strategy is given in Figure 11. It is seen that the strategies 1 and 3 results in a close machining time, whereas strategy 2 takes about 30% longer machining time. One important conclusion from Figure 11 is that, using deep but slow cuts, especially at roughing stage leads to shorter machining times.

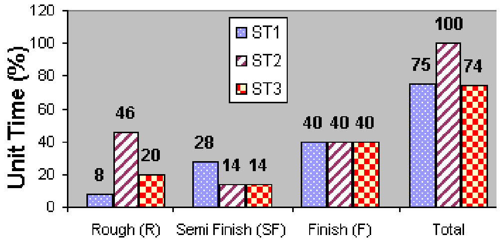


Figure 11: Comparison of normalized machining time.

7. Discussion and Conclusion

In this study, strategy comparison and selection for multi axis milling operations through process modeling is investigated. Cutting forces, tool deflections and process stability at different stages of machining of a workpiece are simulated using previously developed process models. Then, the available operation types and combinations of those are identified as candidate strategies. In simulation of a machining cycle the updated in-process workpiece geometry is used in order to see the effect of the selected operations at each stage on the whole machining strategy. Three representative strategies are compared and it is observed that utilizing high cutting depths with slower speeds and feeds, where possible, leads to shorter machining times for the application considered. It is also shown that process models are good tools in order to compare and select machining strategies for a given workpiece geometry. The estimation and consideration of part deflections at each stage for strategy comparison is currently under investigation.

Acknowledgement

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