Monolithic Formula One Artistic Machining Project Report

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Executive Summary

The objective of the Monolithic Formula One Racer Project is to machine a small scale replica of a McLaren Mercedes Formula One Racer, possessing excellent surface quality without the use of post-milling polishing processes. Originally the solid model was designed for a piece-wise manufacturing process; however as a monolithic 3-axis work piece, several areas were not accessible and therefore translated into regions with poor surface quality. Through the implementation of a systematic optimization process, multiple versions were produced. Each successive version possessed improved overall surface quality in addition to decreased total machining times. In order to meet the objectives of the Monolithic Formula One Racer Project, many challenges were encountered. For purposes of clarity the major challenges and solutions are listed as follows:

Project Challenges

- Limited time due to my undergraduate engineering course work
- Monolithic design limited tool access to many workpiece surfaces
- Complex model geometry with extensive curvature
- Highly accurate, manually indexed fixtures needed to be designed
- Highly precise and efficient toolpath creation and implementation
- Utilization of small tools; as small as Ø0.3mm endmill
- High precision stock material preparation requirements

Resulting Solutions

- Systematic approach maximized my available time
- High precision, ground stock material
- CAD model redesign for increased manufacturability
- Extensive CAM simulation utilized for toolpath and access verification
- Anti-collision simulation mitigated small tool breakage during prototyping
- Custom fixture allowed maximum access to workpiece features
- Piece-wise, region specific finishing allowed for surface quality and machining time optimization
- Optimized cutting parameters through consultation with Sodick application engineers

Procedure

Through the implementation of a systematic optimization process, multiple versions were produced. Figure 1 below illustrates the approach used throughout this project and enabled each of the successive versions to possess improved overall surface quality. Additionally, over-all machining time was greatly reduced.

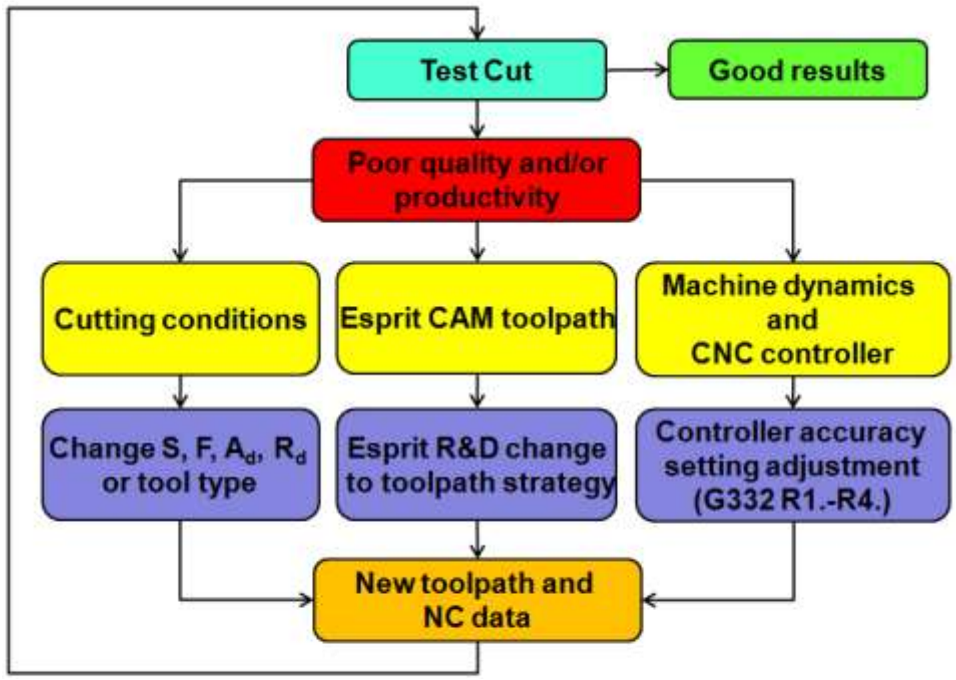


Figure 1: Project Approach Flowchart

Stock Material Preparation

Initially, stock material was prepared on the Sodick MC430L 3-axis mill. Unfortunately a higher level of stock material precision was required in order to prevent tool collision with previously finished surfaces. Through the utilization of an Okamoto ACC6-18DX3 surface grinder, stock materials were prepared with micron level accuracy. The increased level of stock material accuracy has greatly increased repeatability during toolpath testing. The probability of tool collision, due to improper workpiece post-index positioning has also been greatly reduced.

Fixtures

Initially the Monolithic Formula One Racer was machined directly in a vise. This increased the amount of setup time due to a lack of repeatability in positioning. Additionally the stock material was easily deformed due to excessive holding pressures which lead to machining errors upon indexing. Because this project was limited to 3-aixs milling, indexing was required for each of the four sides. In order to ensure repeatability upon indexing and to maintain geometric accuracy, a custom designed fixture was created, as seen in Figures 2 and 3 below.

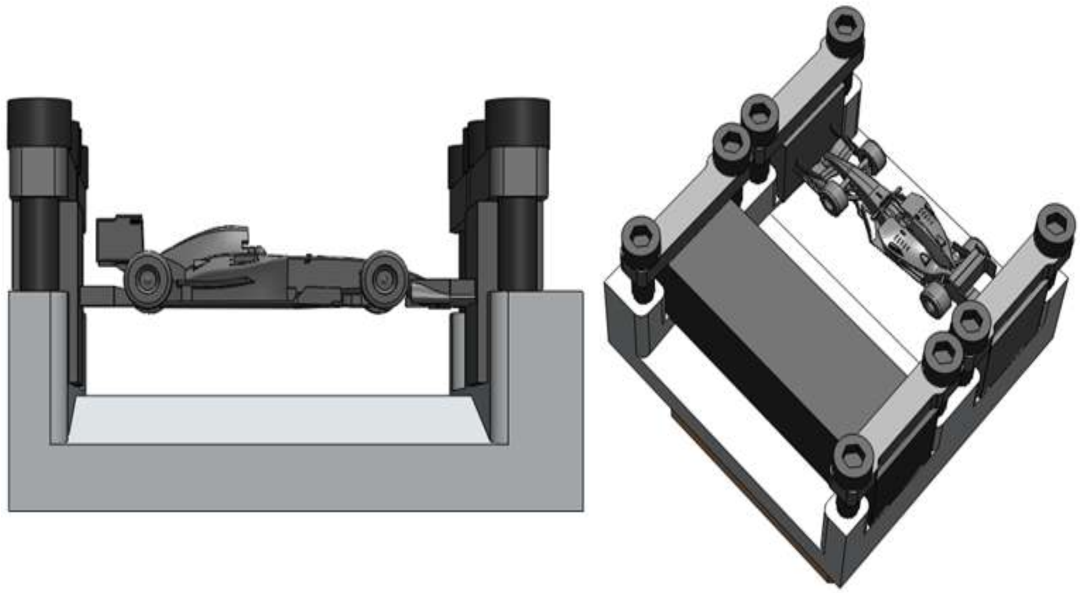


Figure 2: 1st Generation Custom Fixture Solid Model Assembly

Figure 3: 1st Generation Custom Manually Indexing Fixtures In Use

After initial prototyping, a total of 20 1st generation fixtures were created. Upon near-continuous production of 40mm F1 Racers it was realized that the 1st generation fixture lacked the durability required for continuous production and the bracketing system hindered the rigidity of tooling due to the required tool overhang.

In order to alleviate these and other deficiencies a low profile fixture, as seen in Figure 4 below, was designed and fabricated.

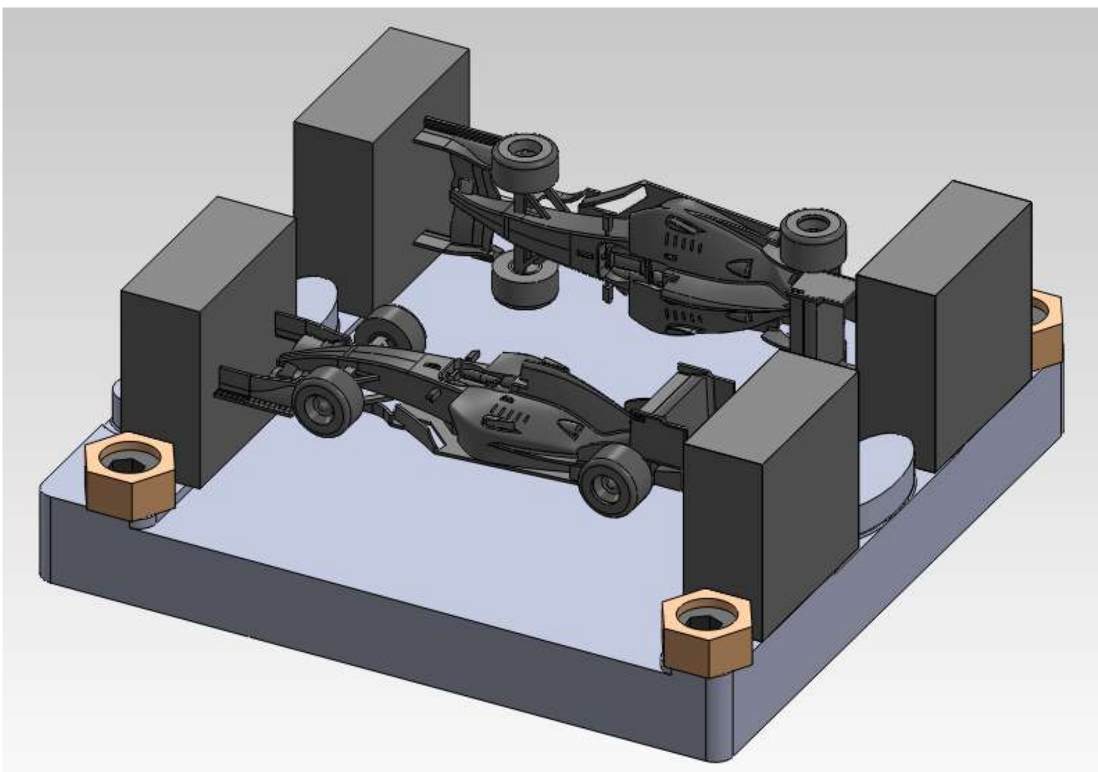


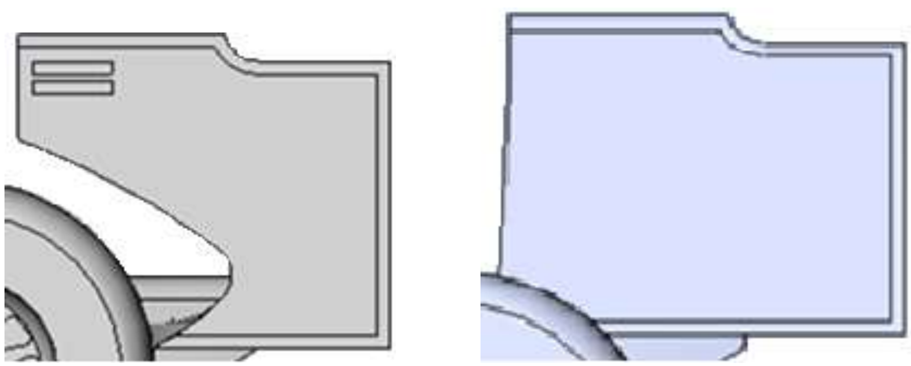
Figure 4: 2nd Generation Custom Manually Indexing Fixture

Appendix A of this report provides is an additional report that explains, in much greater detail, the reasoning, results, and advantages of the 2nd generation fixture.

Solid Model Redesign

Due to a lack of proper tool access in multiple portions of the workpiece, several surfaces had to be finished with non-normal tool posturing. This non-ideal tool posture resulted in the production of a significant amount of chatter and witness lines during machining. Additionally, many open portions of the solid model, although true to the real car, are not achievable in a 3-axis setup resulting in poor surface quality. To mitigate these and other deficiencies, many portions of the solid model were redesigned in order to enhance the overall appearance of the finished workpiece. Figures 5 thru 8 below are examples of some of the alterations made.

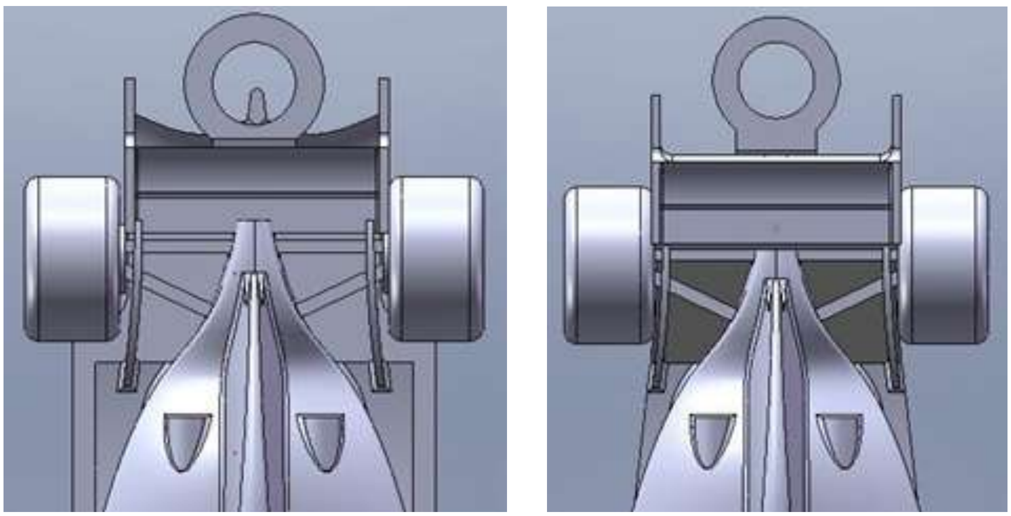
In order to address non-normal to Z-axis surfaces, slight angles were added to vertical surfaces, resulting in enhanced surface quality. As seen in Figure 5 below, the open portion of the rear wing was not accessible at this small of a scale and was therefore filled in.



(Original) (Improved)

Figure 5: F1 racer rear wing.

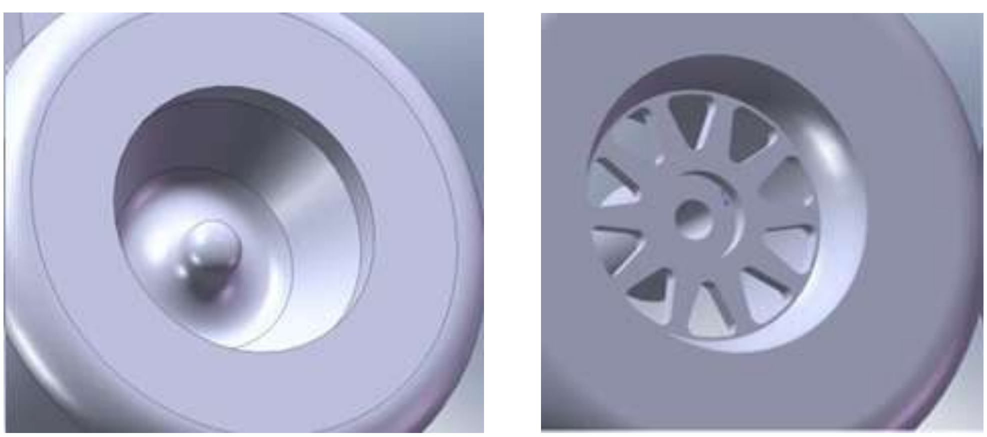
With its open-wheel format, the tires of a Formula One car are one of their most distinct features. Therefore, the wheel and tire surfaces were of particular interest. Previous solid model versions incorporated features that are present in the real car but unfortunately would not allow for continuous contact finishing toolpaths and the surfaces they provide. As seen in Figure 6 below, a portion of the aerodynamic under-tray was removed in front of the rear tires, which allows for a continuous finishing operation and consequently greatly increased surface quality.



(Original) (Improved)

Figure 6: Aerodynamic Under-tray Alterations

A spoke design, as seen in Figure 7 below, was created in order to increase the overall geometric complexity and to enable the use of smaller tooling. This increase in detail constitutes a dramatic increase in complexity due to the small scale of rim features.



(Original) (Improved)

Figure 7: Enhanced Rim Design.

The addition of a driver as seen in Figure 8 below is one of the most noticeable additions to the solid model. This alteration serves two purposes, that of increased complexity and reduced machining time through a decrease in material removal required.

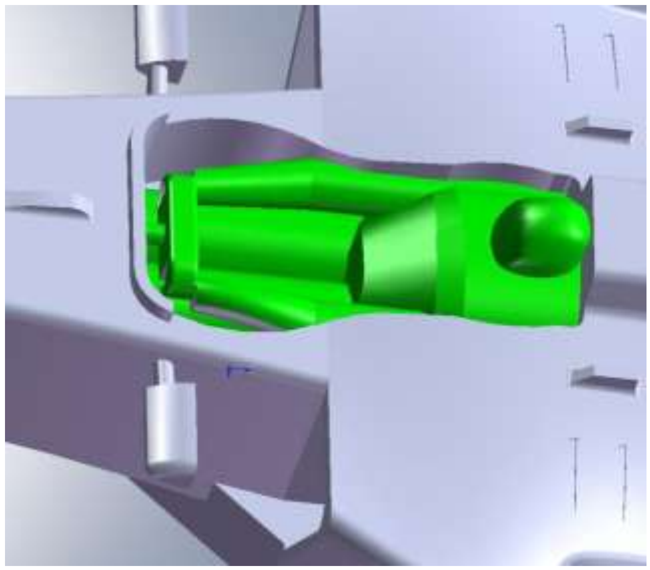


Figure 8: Added Driver Detail

Tool Selection

Tool selection was made through the use of a systematic process beginning with the solid model. Initially, workpiece geometric elements such as corner radii, pocket depth, and curvature dictated the size and type of the required finishing tool. As seen in Figure 9 below, a NS Tools NHB-2 R.5x8 ball endmill was selected for the majority of finishing operations. It provided excellent surface quality and material removal rates while enabling accesses to the many small pockets found in both the front and rear suspensions of the workpiece. Secondly, tools were selected working backwards from finishing to roughing. Semi-finishing tools capable of preparing the optimal amount of stock material required by the finishing tool's depth of cut were next selected. Lastly, roughing tools were selected for maximum rigidity and material removal rate.

Tool	R0.5 ball end mill
Tool overhang	20 mm
Spindle speed	32,000 rpm
Feedrate	1600 mm/min
Depth of cut	0.08 mm, 0.03 mm
Stepover	4%, 2%

Figure 9: Top Side Finishing Tool

Finishing Toolpath Enhancements

Increases in finished surface quality can be attributed most directly to the use of region specific finishing strategies. Initially one Z-level finishing operation was utilized with limited results. This strategy was time consuming and required sacrifices to be made in certain areas when multiple regions were found to have poor surface quality. Additionally this method produced large toolpaths that required longer time periods to test, alter, and retest. By creating individual toolpaths for specific areas, as seen in Figure 10 below, the process of determining an optimized solution was obtain in much less time. Less time is spent assessing surface quality tradeoffs necessitated by one large toolpath. Additionally, due to the relatively small individual toolpaths, test cuts are significantly shorter to create and run. Once tested, these individual toolpaths were combined during post processing.

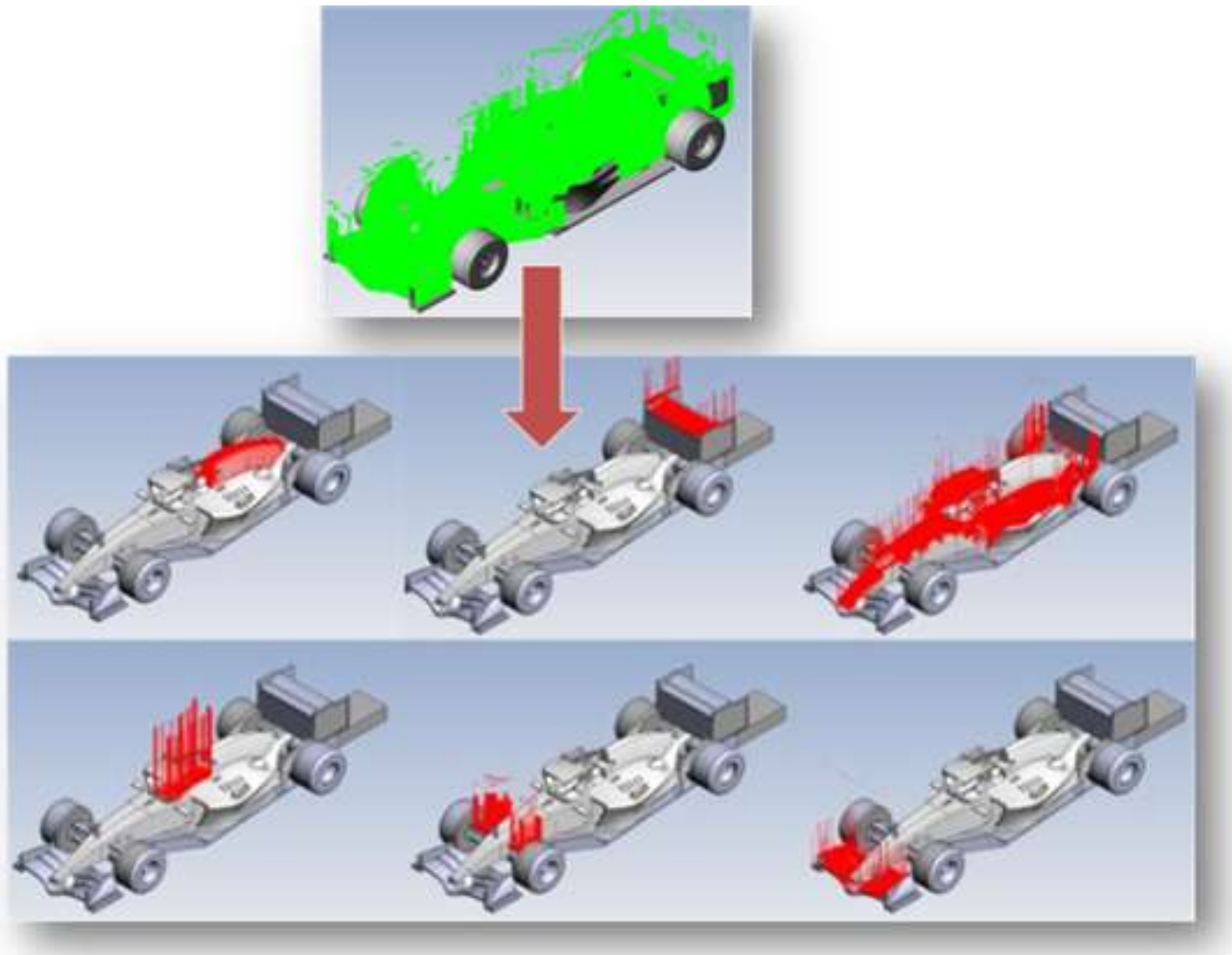


Figure 10: Region Specific Finishing Toolpaths

Cycle Time Reduction

The current version of the Monolithic Formula One Racer has seen some of the highest reductions in machining time. The overall machining time per car is currently 3.54 hours. This represents a reduction of 22% or 56 minutes over the previous version. As seen in Table 1 below, the majority of time savings occurs on the side and bottom indexes.

Table 1: Comparison of Cycle Times

	Current (min)	Previous (min)	Reduction
TOP	**111**	**114**	**2%**
SIDES	**34**	**54**	**37%**
BOTTOM	**16**	**29**	**46%**

The reduction in machining times can be attributed to three main developments. Firstly, the solid model, as seen in Figure 11 below, was set lower in the stock material.

This lower position of the solid model allows for a great portion of material to be removed during the top roughing operations. This significantly decreases the amount of material removed during the left, right, and bottom roughing operations causing the large reduction as seen in Table 1 above.

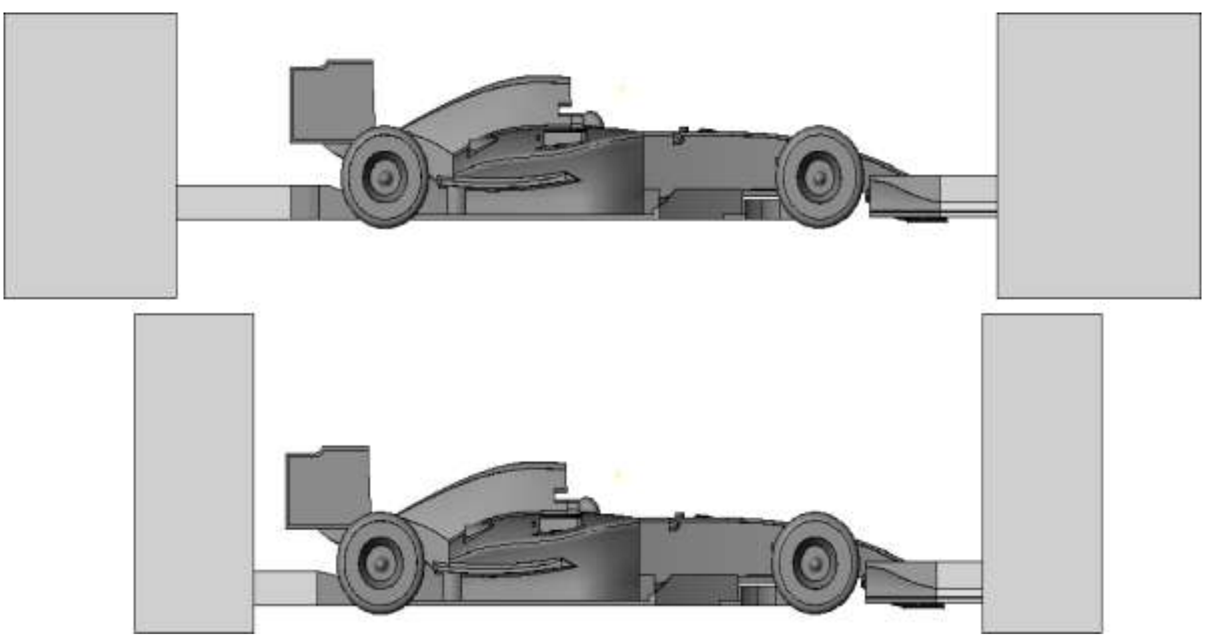


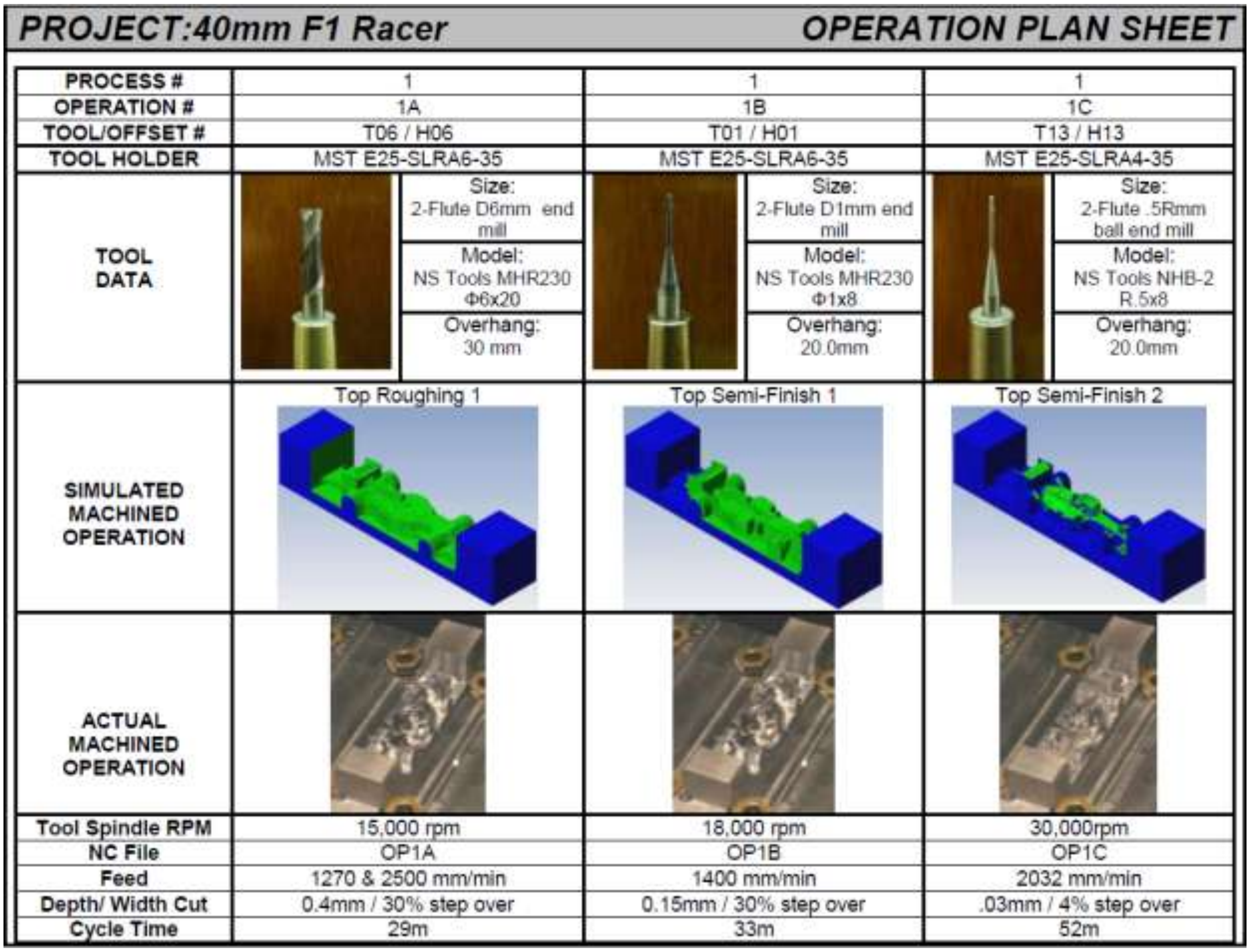
Figure 11: Alteration to Model Setup

Secondly, feedrates of particular semi-finishing operations have been increased by as much as 200% through a process of repeated toolpaths of incrementally smaller depths of cut with the same tool. As this process advances smaller stepovers, in combination with lesser depths of cut, approximate curvature in less time then would be required using a smaller tool. This process decreases time spent changing tools and facilitates allow for higher overall material removal rate (MRR) per unit time. In this way larger tool's MRR are exploited as much as possible before smaller tools are utilized. Additionally, the Increases in tool rigidity, made possible by the new low profile fixture, allow for more aggressive cutting conditions.

Thirdly, though a reduction in the size of the initial stock material, the total amount of material to be removed was reduced and consequently overall machining time was greatly decreased.

Process and Operation Planning

Before primary machining begins, each of the tasks required for machining, including tooling, coordinate axis, feeds, and speeds are organized into a Process and Operation Plan (POP). A portion of the POP for the 40mm Aluminum Monolithic Formula One Racer is show in Figure 12 below.



PROJECT:40mm F1 Racer	OPERATION PLAN SHEET		
PROCESS #	1	1	1
OPERATION #	1A	1B	1C
TOOL/OFFSET #	T06 / H06	T01 / H01	T13 / H13
TOOL HOLDER	MST E25-SLRA6-35	MST E25-SLRA6-35	MST E25-SLRA4-35
TOOL DATA	Size: 2-Flute D6mm end mill; Model: NS Tools MHR230 Φ6x20; Overhang: 30 mm	Size: 2-Flute D1mm end mill; Model: NS Tools MHR230 Φ1x8; Overhang: 20.0mm	Size: 2-Flute .5Rmm ball end mill; Model: NS Tools NHB-2 R.5x8; Overhang: 20.0mm
SIMULATED MACHINED OPERATION	Top Roughing 1	Top Semi-Finish 1	Top Semi-Finish 2
ACTUAL MACHINED OPERATION			
Tool Spindle RPM	15,000 rpm	18,000 rpm	30,000rpm
NC File	OP1A	OP1B	OP1C
Feed	1270 & 2500 mm/min	1400 mm/min	2032 mm/min
Depth/ Width Cut	0.4mm / 30% step over	0.15mm / 30% step over	.03mm / 4% step over
Cycle Time	29m	33m	52m

Figure 12: Portion of the 40mm Process and Operation Plan

The information collected during prototyping and contained in the POP is later used to organize and further optimize the machining process. The machining times are particularly helpful in organizing the labor time required for setup and indexing required. An additional advantage of the POP is the relative ease in which complex, multi-process machining setups can be communicated to those not familiar with a particular project. This is used to efficiently distribute lab time and machine resources within the restriction applied by my undergraduate engineering class work.

Mass Production and Time Studies

Upon review of my work by Sodick, the IMS lab was given a Sodick HS150L, 3-axis machining center equipped with an Automatic Workpiece Changer (AWC) as seen in Figure 13 below. The addition of this mass production style machine allowed for a further expansion of the Monolithic F1 Project. In order to fully utilize the capabilities of the HS150L's AWC, macros were created allowing for the production of 40 cars per batch in near continuous operation. Employing process optimization techniques made possible by the process of POP creation, burr reduction fixture features, and NC macro creation, I have minimized the amount of human labor required for near constant operation.

Figure 13: Sodick HS150L AWC In Operation

The machining times collected in creation of the POP were utilized in the creation of a planning spreadsheet. As seen in Figure 14 below, an outline of machining time dynamically depicts the operational time required for various batch sizes of 40mm Monolithic Formula One Racers in hours and days.

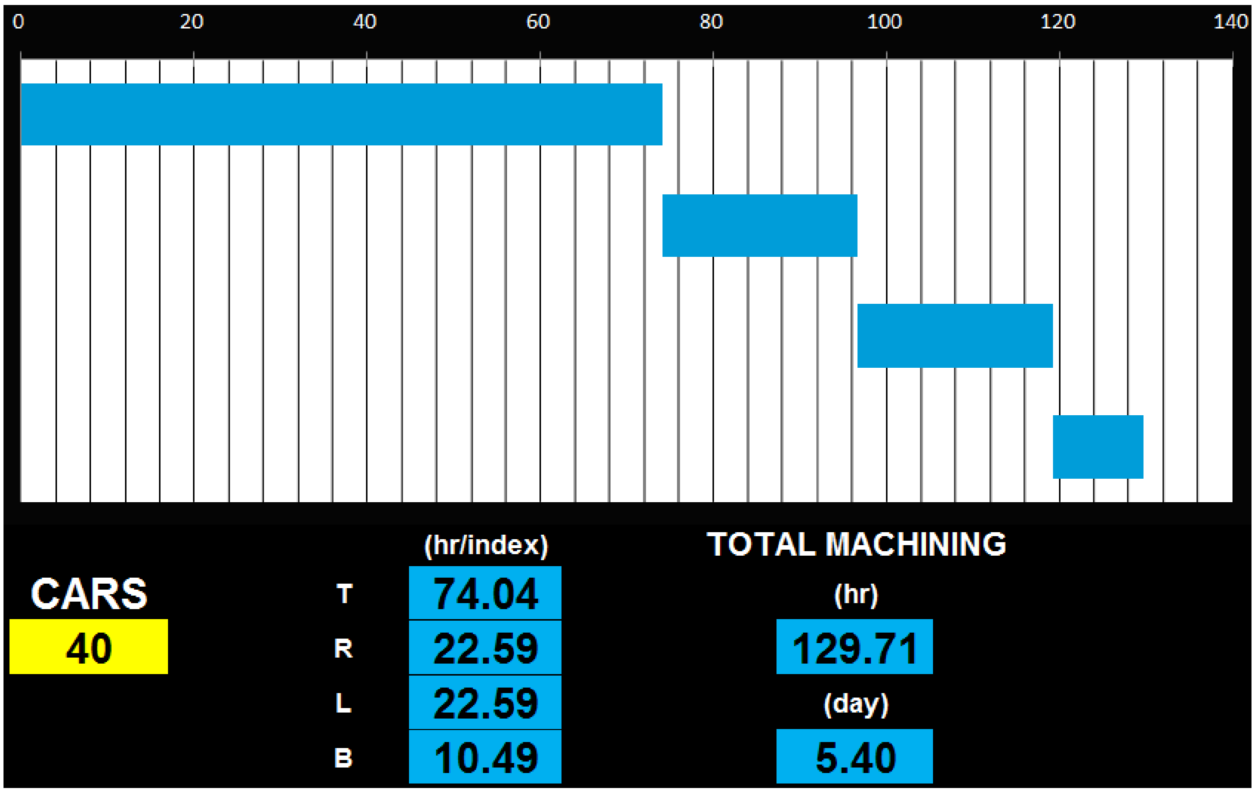


Figure 14: Machining Time Production Study

Multiple Material Studies

In order to expand my understanding of machining, portions of the Monolithic Formula One Project have focused on the milling of multiple materials including Aluminum, Brass, Mild and Hardened Steels. Figures 15 and 16 below are examples of the brass and mild steel prototypes.

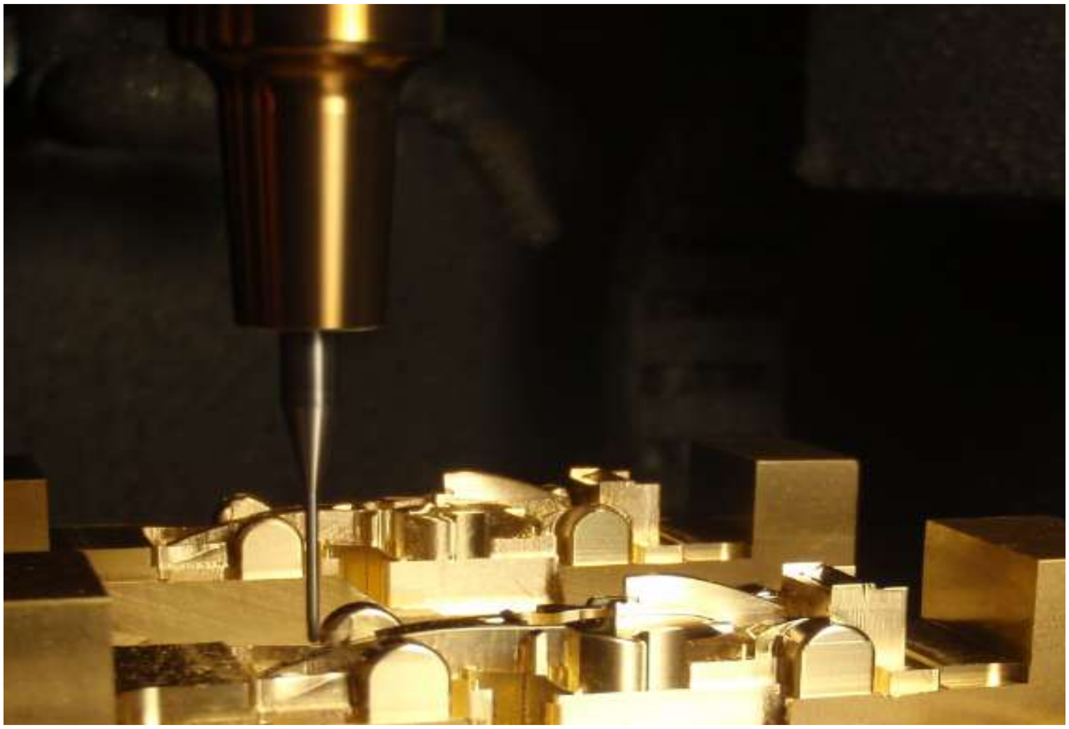


Figure 15: Top Finishing of Brass 40mm F1 Racer

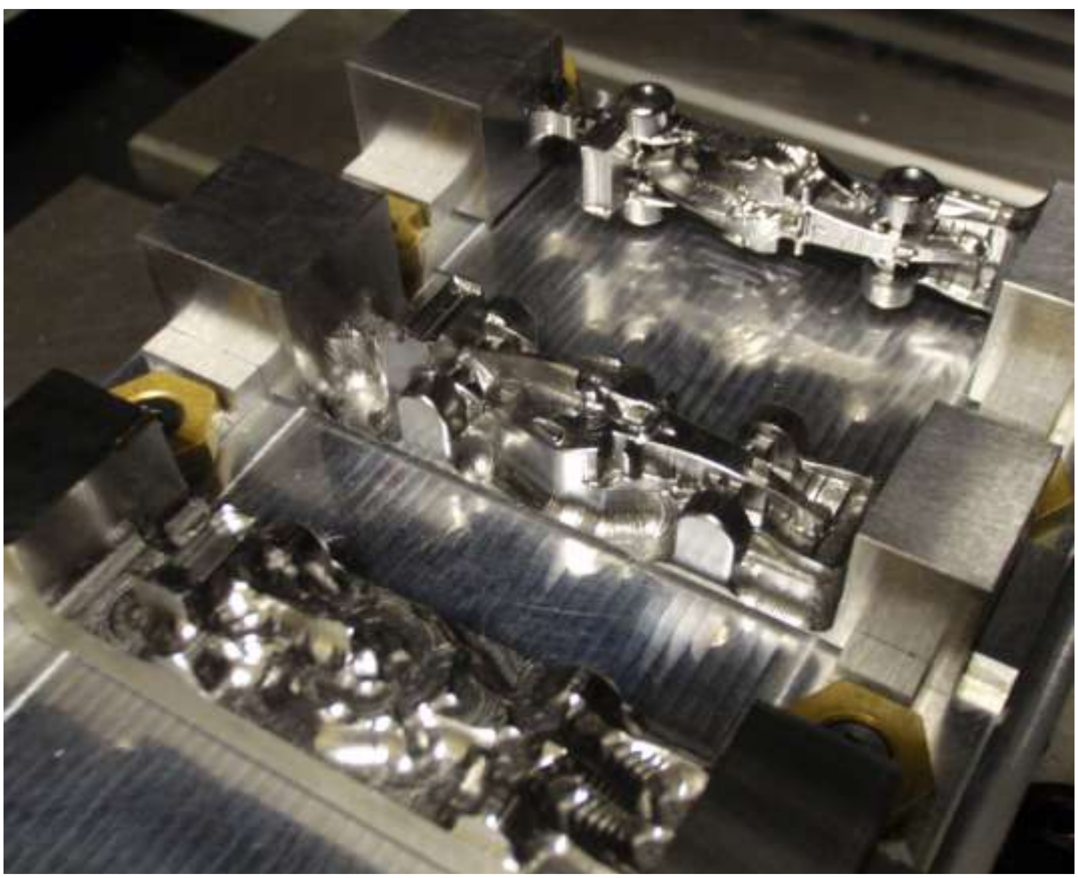


Figure 16: Prototyping of Mild Steel 40mm F1 Racers

The latest version is made of Stavax, a premium grade stainless tool steel widely in used in the mold making industry. As seen in Figure 17 below, the 2nd generation fixture is currently being utilized for 40F1 prototyping.

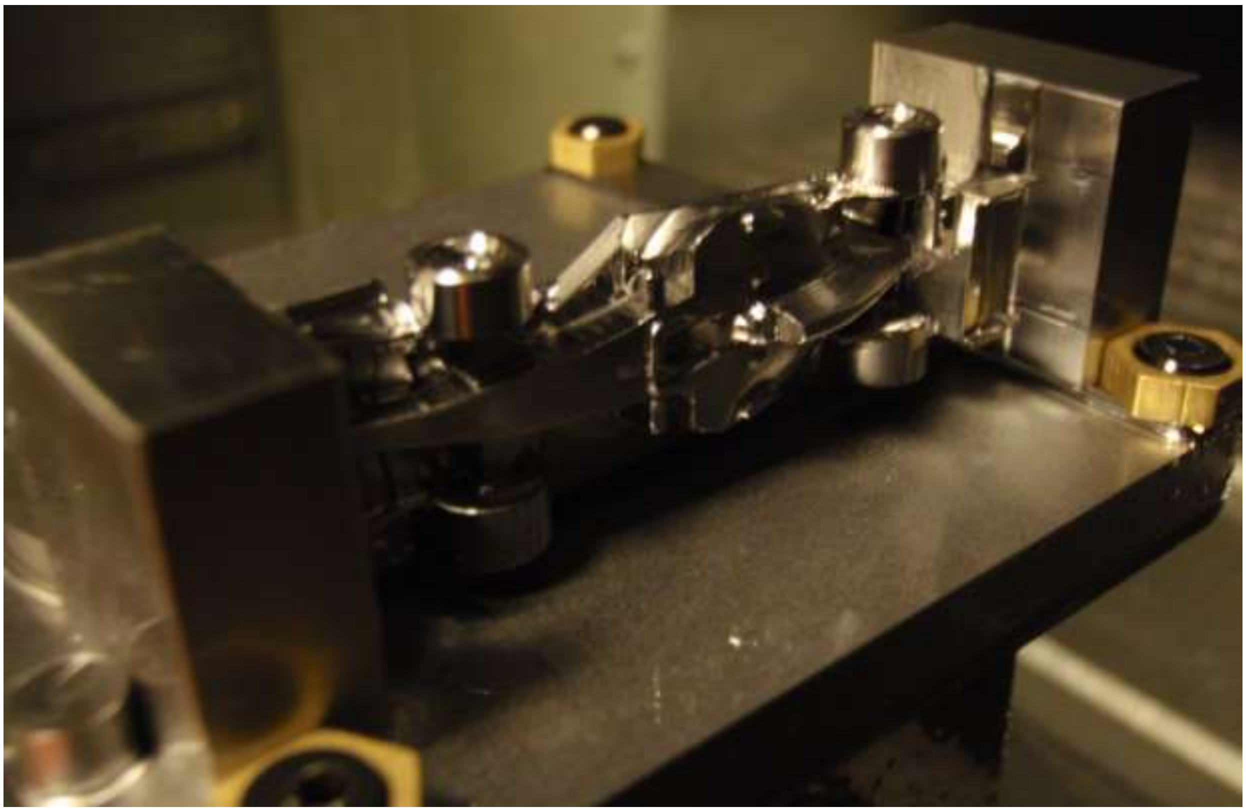
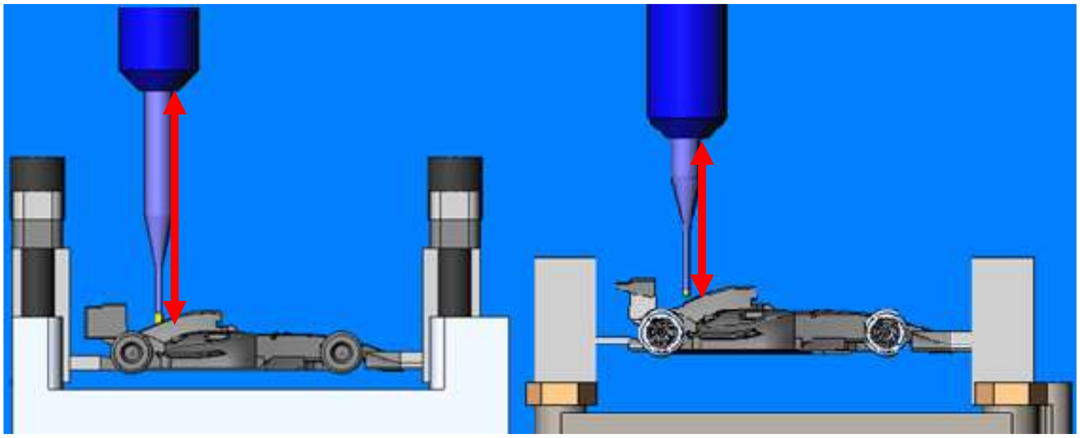


Figure 17: Stavax Monolithic Formula One Prototyping

Through the elimination of the retention brackets, utilized on the previous generation, the current Stavax based 40F1prototype takes advantage of more ridged tooling. The minimization of tool overhang and the resulting increase in tool rigidity has produced improved workpiece surface quality. Figure 18 below, produced with the toolpath analysis feature of Esprit 2012, shows the dramatic decrease in tool overhang made possible by the low profile of the 2nd generation fixture.



Note: NS Tools 1mm Diameter Endmills Shown

Figure 18: 1st and 2nd Generation Tool Overhang Comparison

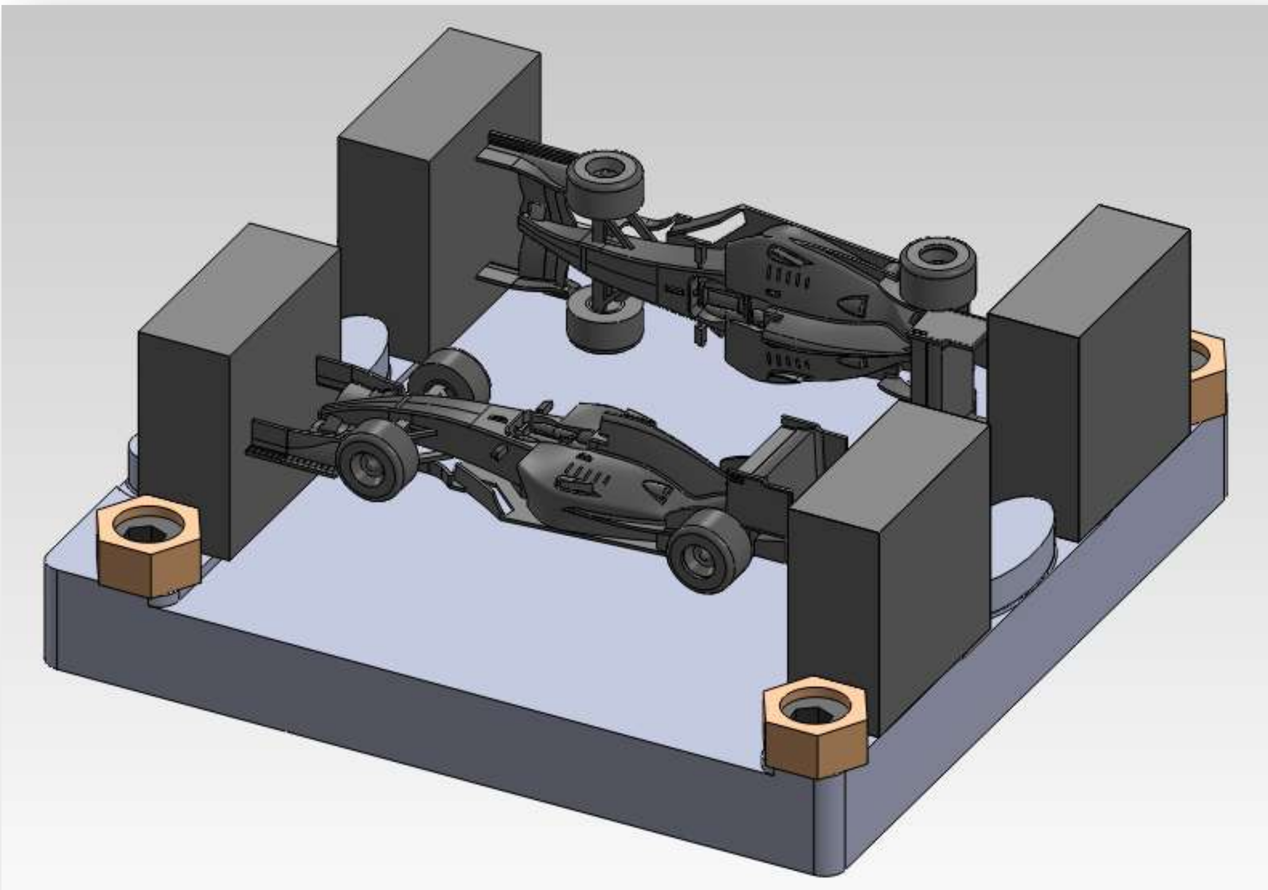
An additional advantage of this low profile design is the reduced chance of collisions between tooling, holders, and fixture elements resulting in a safer machining environment for both operators and equipment.

Conclusion

In order to meet the objectives of the Monolithic Formula One Racer Project, many challenges were encountered. Through the implementation of a systematic development process multiple versions of the Monolithic Formula One Racer were designed, prototyped, evaluated, and optimized. This project provided me with an excellent opportunity to further enhance my understanding of manufacturing techniques and processes. With each successive version, the total machining time was decreased while at the same time achieving greater model detail with greatly improved surface quality. Currently the Aluminum 40mm version is being mass-produced with a target of 1000 racers. At the same time a hardened steel version is being prototyped. Additionally I have begun the process of training new IMS-M Laboratory members to take over this project so that I can pursue my graduate degree in Mechanical Engineering here at the University of California, Davis.

Appendix A:

Comprehensive Fixture Report



Executive Summary

The objective of the Monolithic Formula One Racer Project is to machine a small scale replica of a McLaren Mercedes Formula One Racer, possessing excellent surface quality without the use of post-milling polishing processes. In order to accomplish this objective, custom fixtures were designed to provide repeatable and precise stock material positioning. In addition, the required fixture system needed to be compatible with multiple machining centers. Through the implementation of a systematic optimization process, multiple versions were produced and tested. After initial prototyping, a total of 20 of the 1st generation 40mm Monolithic Formula One (40F1) Racer Fixtures were created. Upon near-continuous production of 40F1 Racers it was realized that the 1st generation fixture lacked the durability required for continuous production. Additionally the following deficiencies were identified:

1st Generation Deficiencies

- The retention bracket design required excessive thread creation during manufacture.
- Indexing operations required too much time due to the cumbersome nature of the retention bracket design.
- Tooling rigidity was compromised due to the excessive height of the retention bracket assembly.
- Under continued use, the threaded aluminum interfaces showed signs of degradation which comprised workpiece holding.

A 2nd generation fixture design was created. The following approaches were taken to mitigate or eliminate the deficiencies identified with the 1st generation design:

2nd Generation Features

- Fixture production time was significantly reduced through the utilization of 4 threaded features instead of 8.
- Dowel pins were added to the Erowa connector side of the fixture to increase its axial positional accuracy.
- Mitee-Bite toe clamps eliminated the need for retention brackets.
- Indexing time was reduced by more than 50% through Mitee-Bite utilization.
- Decreased thread degradation facilitated by the use of steel as the fixture material instead of aluminum.
- EDM elements removed and therefore simplified fixture creation.
- A lower overall fixture profile dramatically increased tool rigidity while still enabling tool access to machined features.

The following sections of this report outline the features and advantages of the 2nd generation 40F1 Racer Fixture and its role in the ongoing incremental improvements made to the 40F1 Racer Artistic Machining Project.

Fixture Background: Previous 40F1 Racer Fixtures

Initial 40F1 Racers were machined directly in a vise. This increased the amount of setup time due to a lack of repeatability in positioning. Additionally, the stock material was easily deformed due to excessive holding pressures resulting in workpiece distortion and thus machining errors upon indexing. Because this project was limited to 3-axis milling, indexing was required for each of the 40F1's four sides.

Upon the generous donation of the Sodick HS150L 3-axis high speed milling center to the UC Davis IMS-M Laboratory, it was decided that the 40F1 Racer Project would fully utilize the mass production capabilities of its 20 position Automatic Workpiece Changer (AWC) while still allowing for machining with the Sodick MC430L milling center. The capability to sustain near-continuous machining provided an opportunity to enhance my undergraduate engineering education and help to acquire a more industrial level understanding of manufacturing processes and techniques.

A major design criterion of the Monolithic Formula One Racer Fixture was the AWC of the Sodick HS150L. As seen in Figure 1 below, the overall dimensions were restricted to a length and width of only 70mm. This is quite restrictive as a result of the workpiece's length of 65mm. A combined fixture, stock materials, and Erowa connector weight of less than 3kg was an additional design limitation.

Figure 1: Sodick HS150L Work Size Limit

Labor time and other production costs are critical to all manufacturing projects. The need to minimize the total machining time per unit dictated the two cars per fixture that were utilized in both the 1st and 2nd generation fixture designs. As seen in Figure 2 below, the 1st generation fixture used standard fasteners in combination with EDM cut elements to create workpiece retention brackets. The AWC requires 1.5 minutes to install or remove a fixture. When a full run of forty 40F1 Racers is setup for machining, each of the 20 fixtures are filled to capacity, therefore a fully utilized machining run requires one full hour dedicated to only switching out workpieces.

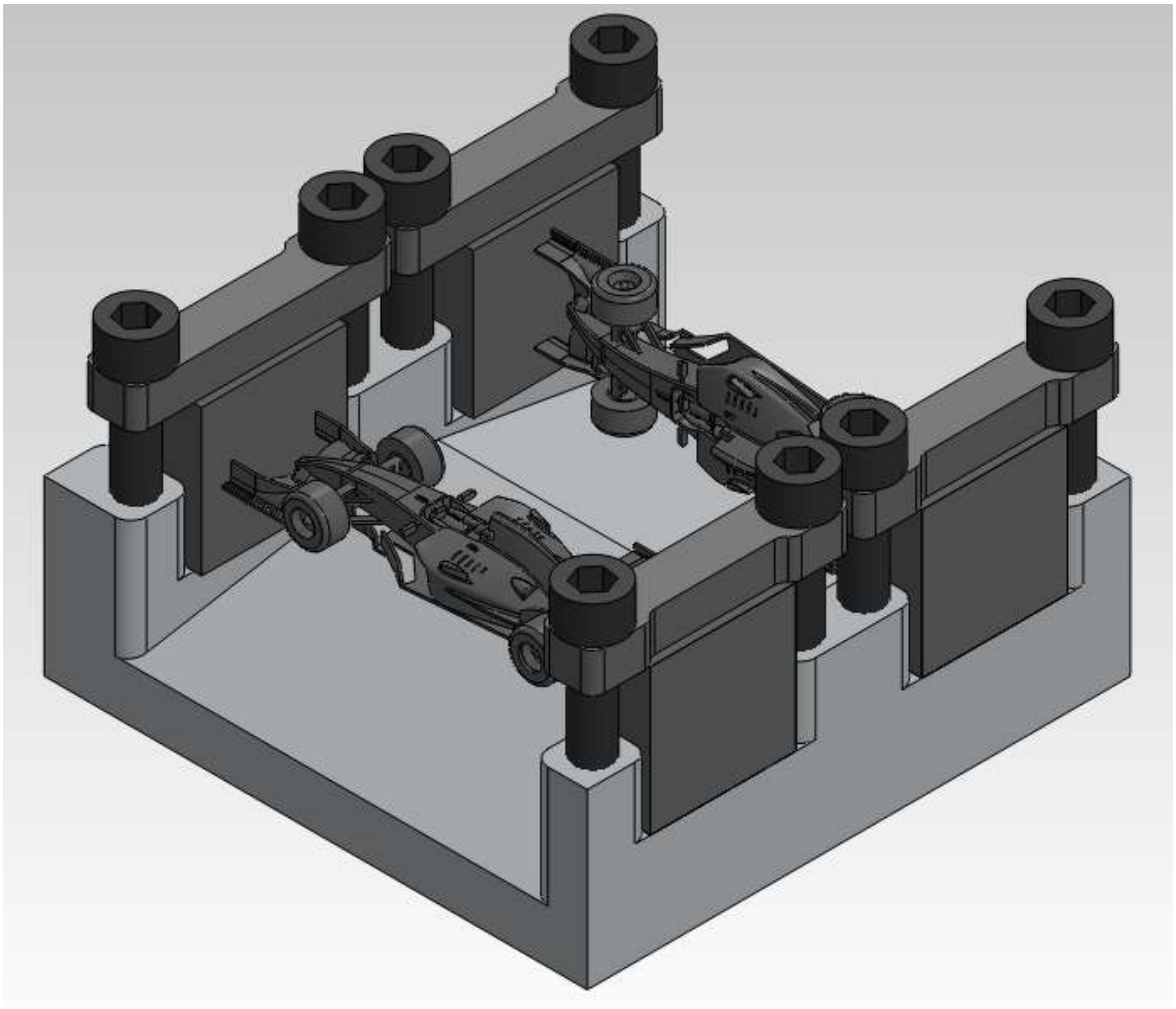


Figure 2: 1st Generation 40F1 Racer Fixture Solid Model Assembly

Throughout initial prototyping and production, the 1st generation 40F1 Fixture performed well and therefore a total of 20 fixtures were produced, a portion of which can be seen in Figure 3 below.

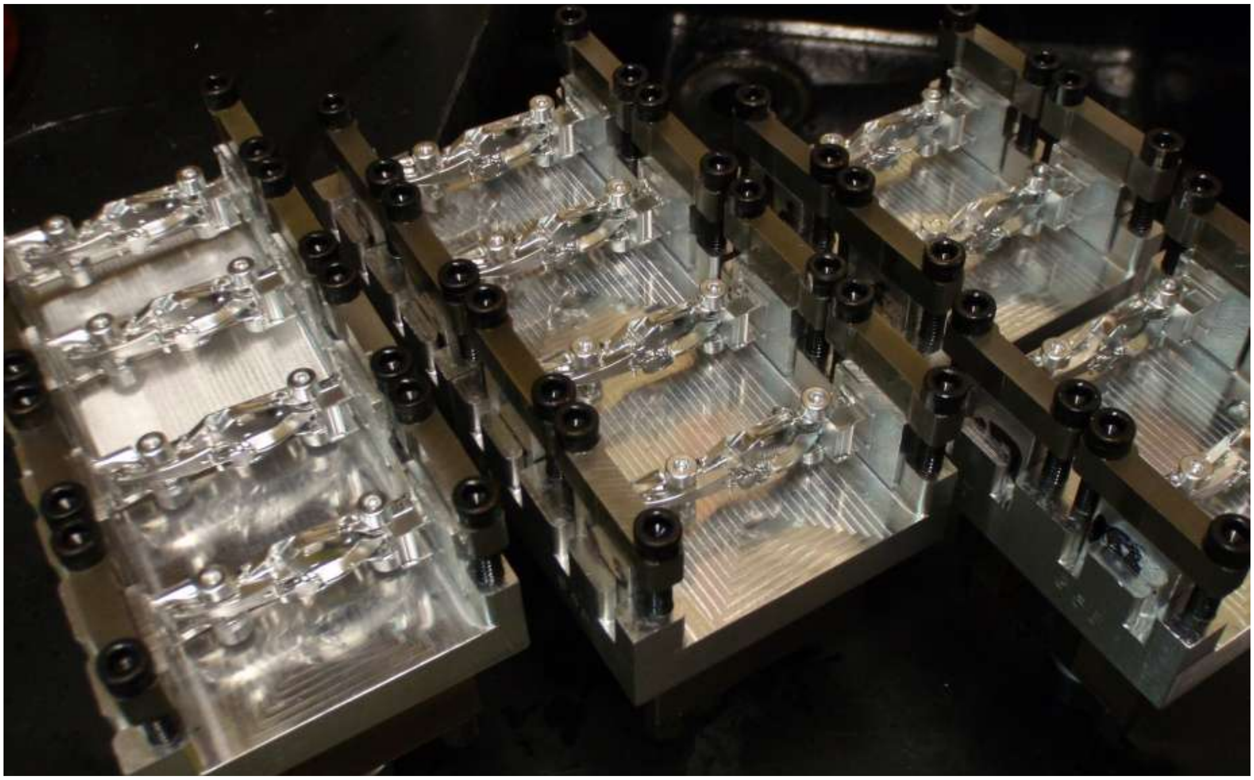


Figure 3: 1st Generation Monolithic F1 Racer Fixtures In Use

The retention bracket design used in the 1st generation fixture did provide stable workpiece holding; however there were multiple deficiencies found under continued usage. The two major problems encountered were the degradation of the fixture treads and the excessive labor time required for each of the four indexing operations, per car, during 40F1 Racer production. Labor time is of particular importance to the academic environment in which this project is set. The availability of labor time is greatly limited due to my undergraduate course work. Testing determined that the average time required for a single indexing operation was two minutes. This translates into a total of four hours of indexing for a full run of 40F1 Racers. The reduction of this required labor during indexing was a critical objective of this redesign project.

Current 2nd Generation Monolithic Formula One Racer Fixture

The following section discusses the improvements to and the motivations for the redesign of the Monolithic Formula One Fixture in greater detail. As seen in Figure 4 below, the 2nd generation fixture is the result of a total redesign.

The following improvements and features were added to the 2nd generation 40F1 Racer Fixture:

- Reduced fixture manufacturing cost and time.
- Increased threaded feature life.
- Increased workpiece alignment accuracy.
- Dramatically reduced indexing labor time.
- Steel and Aluminum 40mm F1 Racers can be machined in the same fixture.
- Compatible with both the Sodick HS150L and MC430L milling centers
- Reduced opportunities of tool, holder, and fixture collision.

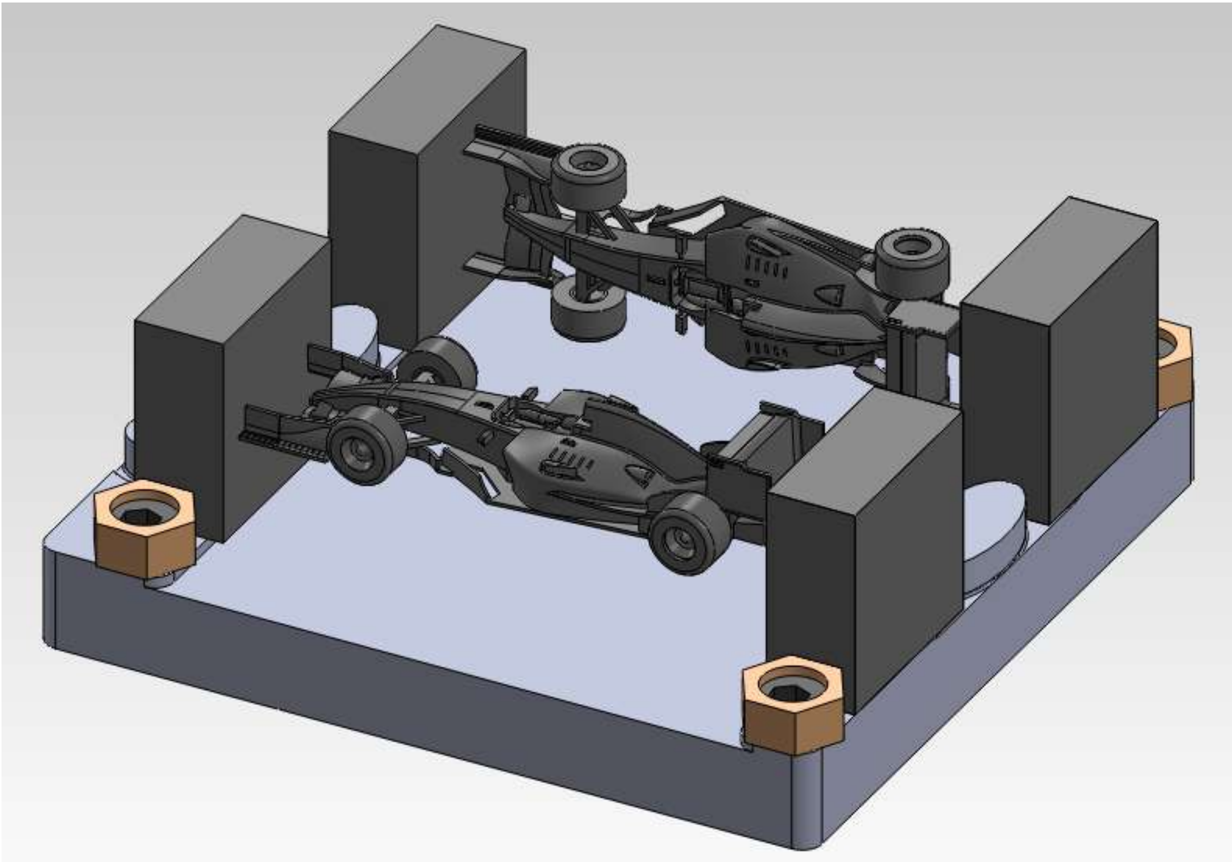
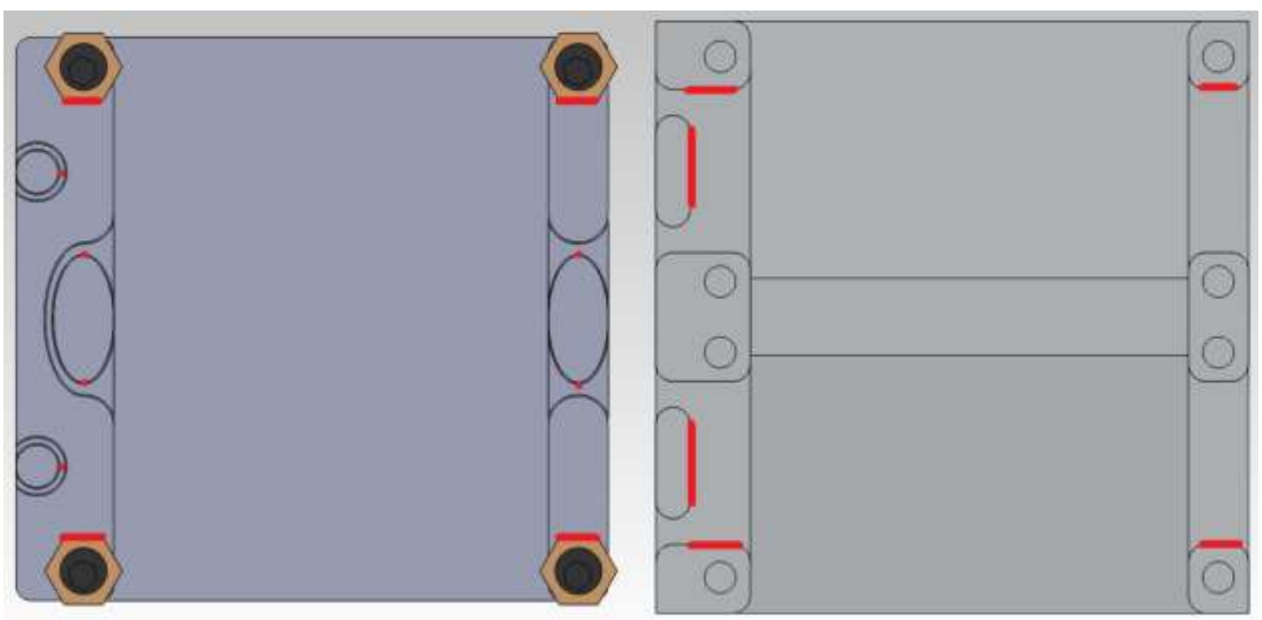


Figure 4: 2nd Generation Monolithic F1 Racer Fixture Solid Model Assembly

The two major alterations, when compared to the previous fixture, are the elimination of the retention bracket system and the utilization of a steel-fixture material instead of aluminum. Additionally, Mitee-Bite tow clamps were utilized to provide workpiece retention and facilitated the reduction of fixture production time by the elimination of half of the total required threaded elements. Mitee-Bites also allowed for a more reliable holding force in much less space than the previous system.

The low fixture profile made possible by the implementation of Mitee-Bite tow clamps reduced the overall fixture stock material size by half and therefore helped to reduce material costs. With its low profile design, the 2nd generation fixture can be machined in less time than the 1st generation fixture despite the lower material removal rates of milling steel.

The 2nd generation fixture was designed to further minimize workpiece machining errors due to misalignments caused by foreign material. Chips and other materials encountered in the machining process can inadvertently be lodged between the fixture and workpiece contact surfaces during indexing. The extra time required to check for and clean off this material helped to increase the overall labor time of production. Through the extensive utilization of curved contact surfaces the likelihood of misalignment caused by foreign material has been greatly decreased. As seen in Figure 5 below, a reduction of contact area of approximately 60% was achieved by this new design.

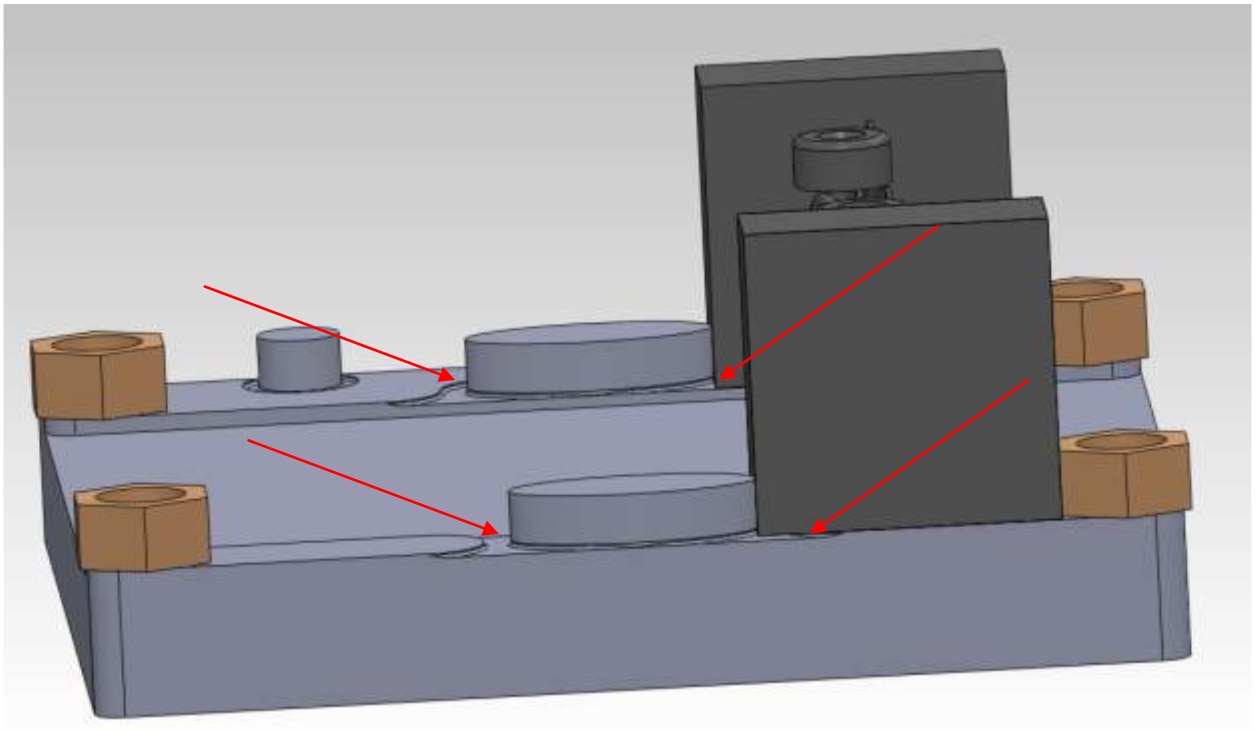


2nd Generation **1st generation**

Note: Red Areas Highlight Workpiece Contact Surfaces

Figure 5: 1st & 2nd Generation Contact Area Comparison

A further enhancement found in the 2nd generation fixture is the addition of recessed areas. These recesses help to prevent misalignments caused by workpiece edge burrs created during machining and can be seen in Figure 6 below.



Note: Recessed areas prevent misalignment caused by burrs and foreign material

Figure 6: 2nd Burr Reduction Features

These burrs are created during the milling of adjoining sides and can prevent proper alignment producing errors in machining. Manual removal of burrs during the indexing process is possible; however it produces an increase in labor time associated with product production and was therefore reduced.

Conclusion

Through the implementation of a systematic optimization processes, extensive computer based CAD and CAM simulation, physical testing, and observation, multiple 40F1 fixture versions were produced. Each successive version was a significant improvement with respect to decreases in manufacturing time, required labor, the occurrence of burr and foreign material induced errors, likelihood of collisions, and production costs. Additionally tool rigidity, workpiece alignment precision, and repeatability were simultaneously increased.

These improvements have helped to make the 40F1 Racer Project more robust. This is evident by the added ability to manufacture multiple workpiece materials, and workpiece versions simultaneously. Through allowing for multiple machine tools to be used, while achieving a reduction in the necessary labor costs, the limited time afforded to me during my full time undergraduate engineering studies could be most efficiently utilized. In preparation for my Graduate studies I have started the process of training incoming IMS-M Lab members the necessary steps of designing, prototyping, evaluating, and production that will continue to be required as the 40mm Monolithic Formula One Project continues.